AFAL-TR-79-1002

LASER PUMP LAMPS

Norman C. Anderson

ILC Technology, Inc.
399 Java Drive
Sunnyvale, CA 94086

February 1979

Final Report February 1976 - September 1978

Approved for Public Release; Distribution Unlimited

AIR FORCE AVIONICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

James M. Heitman
Project Engineer
Electro-Optic Detectors Group

Clyde L. Woodard, Chief
Electro-Optic Detectors Group
Electro-Optics Technology Branch

FOR THE COMMANDER

Ronald F. Paulson, Actg. Chief
Electro-Optics Technology Branch
Electronic Technology Division

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFAL/DHO *,W-PAFB, OH 45433 to help us maintain a current mailing list".*

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AIR FORCE/56780/24 July 1979 — 75

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	AFAL-TR-79-1002
2. GOVT ACCESSION NO.	
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle)	LASER PUMP LAMPS
5. TYPE OF REPORT & PERIOD COVERED	Final Report. Feb [redacted]76 - Sept[redacted]78
6. PERFORMING ORG. REPORT NUMBER	R-ILC-77-4/F
7. AUTHOR(s)	Norman C. Anderson
8. CONTRACT OR GRANT NUMBER(s)	F33615-76-C-1029
9. PERFORMING ORGANIZATION NAME AND ADDRESS	ILC Technology, Inc. 399 Java Drive Sunnyvale, CA 94086
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	2028-01-20
11. CONTROLLING OFFICE NAME AND ADDRESS	Air Force Avionics Laboratory (DHO) Wright-Patterson AFB, Ohio 45433
12. REPORT DATE	Feb[redacted]79
13. NUMBER OF PAGES	141
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	139p
15. SECURITY CLASS. (of this report)	Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Lasers
Optical Pumping
Arc Lamps
Alkali Vapor Lamps
Space Communications

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The subject program was undertaken to develop technology for producing a potassium vapor arc lamp with a 3000 hour lifetime. The lamp is to be used as optical pump source in a Nd:YAG laser transmitter as part of a space communications system. The lamp lifetime goal was successfully achieved, a characteristic lifetime of approximately 6000 hours being demonstrated for lamps built late in the program. In addition,

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

388 867

the final lamp satisfied virtually all other design and performance requirements. Most of the effort on the program was directed at developing supporting technology for the lamp. This work included solving problems of basal plane cracking and potassium vapor attack of the sapphire envelope, developing a long-lived cathode, determining the most efficient lamp fill, developing an oxidation protection coating for the Kovar endcaps, optimizing the Kovar-to-sapphire brazed seal design, conducting thermal design proof tests (including simulation of zero-g effects), improving the potassium filling procedure, developing an optimized lamp operating procedure, and conducting vibration tests.

FOREWORD

The work reported herein was performed under Contract F33615-76-C-1029, Project 2028 for the Air Force Avionics Laboratory, Wright Patterson AFB, Ohio. The Air Force technical monitor was Mr. James Heitman (AFAL/DHO-3).

The program was conducted over a nearly three-year period from February, 1976 to September, 1978 in the Advanced Products Group at ILC Technology which is directed by Dr. Leonard Reed.

The program managers were Dr. David Priest and, during the final year, Mr. Robert Anderson. The project engineer and author of this report was Mr. Norman Anderson. Engineering assistance was provided by Mr. Lloyd Fuke and Dr. James Shaw. Ms. Linda Richter was responsible for lamp fabrication and process development assisted by Ms. Pamela Pelikan and Mr. William Warren. Lamp testing was performed by Mr. Martin McCarthy and Mr. Dan Hitesman.

The author gratefully acknowledges the suggestions and support provided by Mr. Heitman and also Dr. R. M. F. Linford of McDonnell Douglas Astronautics Company during the course of the work.

This report was submitted to the Air Force for approval on 14 December 1978.

A

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Con't)

LIST OF TABLES

SECTION I

INTRODUCTION

This is the final technical report on the Space Flight Test System (SFTS) Laser Pump Lamp Development Program. The primary objective of the program was to provide technology necessary to produce a reliable, long-lived (3000 hour) 250 W CW alkali metal laser pump lamp for use in a Nd:YAG space communication laser under development by the Air Force. This objective has been successfully achieved.

The subject program complemented a concurrent subcontract at ILC from McDonnell-Douglas Astronautics Company-St. Louis, the prime contractor for development of the space laser system. The MDAC subcontract was concerned primarily with sequential iterative lamp design improvement while the subject Air Force program accented development of supporting lamp technology. There necessarily was considerable interplay between the two programs; to provide a balanced and complete account of the lamp development effort, work on the iterative design development task is also described in this report.

The report is organized as follows: In Section II a review of prior lamp development work leading up to the present SFTS effort is given. In Section III the designs and life test results for the six lamp iterations produced on the SFTS programs are presented. Accounts of work on various engineering support tasks are given in Section IV. Finally, a review of the final lamp design and performance characteristics is given in Section V.

SECTION II

BACKGROUND

A. Early Work

Initial work at ILC Technology on alkali metal arc discharge lamps for optical pumping of CW Nd:YAG lasers[1-3] was primarily devoted to studies of the effects of lamp design and operational variables on laser pumping efficiency. A significant finding in this work was that lamps filled with a mixture of potassium and rubidium were apparently the most efficient. Consequently, K-Rb was adopted as the baseline fill and remained so until late in the present SFTS program. Early K-Rb lamps employed translucent alumina, drawn tubular sapphire, or cored and polished Czochralski-grown sapphire envelopes and brazed niobium endcaps. The lamps had to be operated in evacuated bell jars, in very pure purged inert gas environments, or in sealed-off fused quartz vacuum jackets to prevent oxidation of the endcaps and brazed seals.

In response to the need for a lamp operable in ambient air and more compact than the double envelope, vacuum jacketed configuration, the protected endseal (PES) design was conceived. In the PES lamp design, hermetic secondary ceramic/metal end enclosures were frit-sealed to the primary sapphire envelope, evacuated, and sealed off to protect the niobium endcaps and brazed envelope seals from oxidation. Early PES lamps were short-lived, primarily because of unreliability of the solder glass frit seals then used. All early lamps were also subject to the problem of "frosting" of the envelope interior surface caused by chemical attack of the sapphire by alkali metal vapor.

B. EFM Phase

K-Rb lamp development at ILC continued as part of the engineering feasibility model (EFM) phase of the Air Force space communications laser program under direct contracts[4,5] and on concurrent subcontracts from GTE-Sylvania (the contractor for laser development) and McDonnell Douglas. In this phase of the work development of the lamp-pumped laser by Sylvania and the lamp itself by ILC were coordinated.

Interim design requirements were established for the lamp. These included an arc gap and envelope bore diameter of 63.5 mm and 5 mm respectively; use of cored and polished Czochralski sapphire for the envelope; a single envelope, air-compatible configuration; and a nominal electrical input power of 250 W. An EFM-phase lamp lifetime goal of 511 hours and 73 operating cycles was also established (this would allow the lamp pumped laser to be operated for seven hours every five days over a one year period).

EFM-phase work initially concentrated on improvement of the PES lamp lifetime. However, early technical problems with PES lamps led to a decision to postpone PES lamp building and instead develop more reliable seals for these lamps. Meanwhile, an alternate single envelope lamp design was introduced which featured nickel endcaps and oxidation resistant brazed seals. A variation of the nickel endcap lamp followed with Kovar alloy endcaps for potentially better thermal cycle durability.

Persistent difficulties in fabricating PES lamps led to the adoption of nickel and Kovar endcap lamps as the primary designs. At the end of the EFM-phase work, average lifetimes for nickel and Kovar lamps were 867 and 630 hours, respectively, in both cases exceeding the 511 hour interim goal. The primary failure mechanisms were oxidation-induced leaks in the brazed seals and endcaps and basal plane cleavage cracking of the sapphire envelopes. One PES lamp of an improved design had been successfully fabricated and life tested, failing in 187 hours.

In addition to the significant improvement in lamp lifetime (with the attendant implication that the 3000 hour lifetime goal was now well within reach), EFM-phase advances included:

- substantial improvement in laser pumping efficiency resulting from the substitution of xenon gas fill for previously used argon.
- reduction in envelope "frosting" resulting from adoption of glove box lamp processing and use of depleted uranium getters within the lamp.
- the development of a lamp fully compatible with a co-designed laser pump cavity.

C. SFTS Phase Objectives

The principal objective on the SFTS-phase programs was to extend lamp lifetime to the 3000 hour program goal. This required that the problems of oxidation-induced seal and endcap leaks and basal plane fracture of the sapphire be solved.

Secondary objectives included refining of the lamp design for complete electrical, mechanical, and optical compatibility with the final space prototype laser pump cavity, investigating variables associated with laser pumping efficiency and improving efficiency if possible, and developing an optimum procedure for operating the lamp.

SECTION III

ITERATIVE LAMP DESIGN DEVELOPMENT

Six sequential lamp design iterations were produced on the SFTS program, each feeding on determinations of failure mechanisms and design deficiencies of previous iterations. This task was, as indicated earlier, a major segment of the concurrent McDonnell-Douglas subcontract. Evaluation of the final, sixth iteration design is incomplete (life testing of this lamp is currently underway at MDAC); nevertheless, this design is expected to satisfy virtually all of the lamp requirements established for the program.

Details of the designs and test results on each are given below.

A. First Iteration

1. Designs

Both nickel and Kovar endcap lamps were constructed and tested in the first iteration. Nickel endcap lamps were made with Type 270 (high purity) nickel seal cups but were otherwise similar in design to the previous EFM phase "latest technology" lamps[6]. It was hoped that the high purity nickel would be more resistant to intergranular penetration by the brazing alloy and thus less subject to subsequent grain boundary oxidation during lamp service. The Kovar lamp end seals were brazed with a combination of zirconium and nickel (so-called "hybrid" seal).

All first iteration lamps were filled with 100% rubidium so that envelope basal plane cleavage cracking, believed to be caused by potassium attack of the sapphire, could be avoided. This would allow determination of lamp lifetimes influenced only by the lamp structural design.

2. Test Results

Two nickel endcap lamps, N6L and N7L, and three Kovar endcap lamps, K21L, K22L, and K24L, were life tested. The results of these tests (Table 1) were disappointing. Endcap leaks developed in the nickel lamps relatively early in life indicating that use of type 270 nickel had not improved resistance to this failure mode. Postmortem metallography on these lamps revealed that the leak paths were in the side walls of the cups in areas penetrated intergranularly by melted braze alloy that had flowed out of the braze joint.

An even shorter average lifetime was obtained for the first iteration Kovar endcap lamps. The telltale presence of hydrated alkali metal on the lamp exteriors at sites on the brazed seal fillets suggested that intergranular oxidation was again responsible for failure. However, metallography did not provide direct evidence of such oxidation. The hybrid seal microstructures appeared to be free of either initial melt phase erosion or subsequent oxide penetration. It is likely that leakage occurred along the marginally bonded interface between the brazement and sapphire in these seals, especially in lamp K24L whose anode end seal parted at the interface during postmortem examination.

TABLE 1

FIRST ITERATION LAMP LIFE TEST RESULTS

Lamp Number	Design Type	Lifetime Cycles	Lifetime Hours	Failure Mode
N6L	Nickel Endcap	43	453	Leaks in cup sidewalls
N7L	Nickel Endcap	42	465	Leaks in cup sidewalls
K21L	Kovar Endcap	3	42	Leak at anode end seal
K22L	Kovar Endcap	5	142	Testing terminated, frosty envelope analyzed by SEM
K24L	Kovar Endcap	21	561	Leak at anode end seal

B. Second Iteration

1. Designs

Second iteration designs included one type of nickel endcap lamp and two types of Kovar endcap lamps. All featured the following design modifications (see Figure 1):

1. Reduction in mechanical mounting surface diameters to 9.53 mm (0.375 in) from the previous 10.8 mm (0.425 in) to comply with the interface requirements of lamp life test fixtures being constructed by GTE-Sylvania at the time.
2. Extension of the weld adapter at the cathode end of the lamp and addition of Kovar sleeve to the anode end, both for the purpose of strengthening the lamp mechanical mounting extensions.
3. Use of pure tungsten cathodes which were expected to be more efficient and to have better long term stability than the cathodes of thoriated tungsten that had been previously used.
4. Use of a 90%K-10%Rb lamp fill instead of the then current 75%K-25%Rb "baseline" fill in anticipation of the forthcoming adoption of the higher potassium composition that was believed to produce a more efficient lamp output.

Following the unsuccessful experience with type 270 nickel in first iteration lamps, type 200 nickel seal cups were used in the nickel endcap lamps. A thinner zirconium brazing washer was also used to reduce intergranular penetration of the nickel by brazing alloy and thus increase oxidation resistance.

Kovar endcap lamps with both hybrid and zirconium-only brazed seals were fabricated in the second iteration. The hybrid seals were modified from those used in first iteration lamps (thicker zirconium and nickel washers were used). Heavier wall

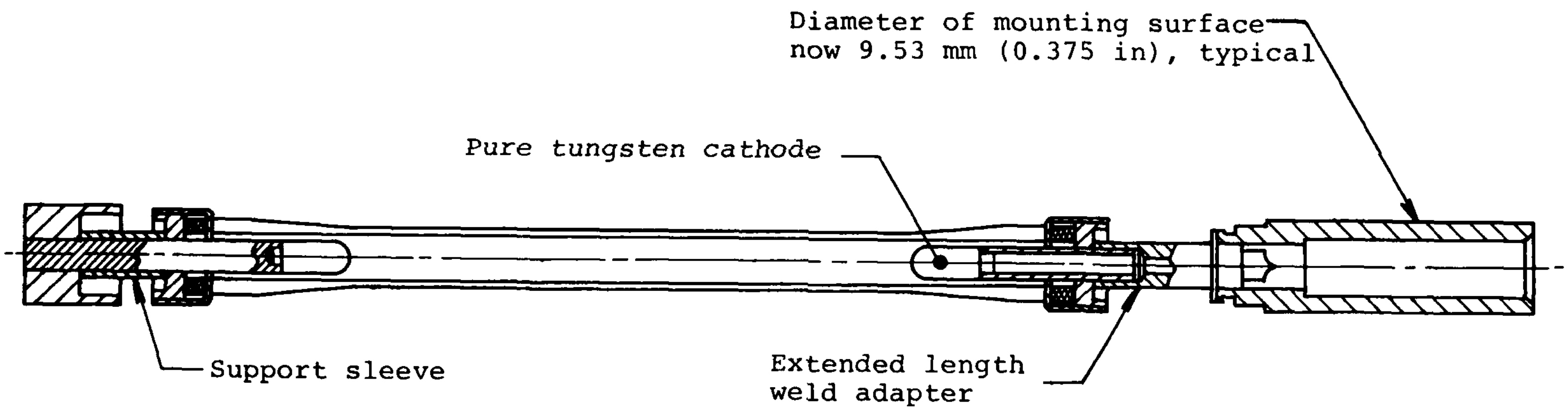


Figure 1. Second Iteration Lamp Design

cups were employed in both Kovar endcap designs, 0.38 mm (0.015 in) thickness compared with the 0.25 mm (0.010 in) cups used previously.

2. Test Results

Ten second iteration lamps were successfully fabricated and put on life test. Life test results (Table 2) indicated that the nickel endcap lamps were relatively short lived despite the use of less zirconium in the brazed seals. Failure in three of these lamps was caused by the familiar intergranular oxidation mechanism indicating that initial penetration by brazing liquid was still significant despite the seal modification. The other nickel endcap lamp, N49L, failed very early in life by pinch-off leakage. During the failure process, the entire pinch-off region had been obliterated by corrosive, oxidized alkali metal, precluding specific identification of the original deficiency.

TABLE 2

SECOND ITERATION LAMP LIFE TEST RESULTS

Lamp Number	Design Type	Lifetime Cycles	Lifetime Hours	Failure Mode
N49L	Nickel Endcap	4	17	Pinch-off leak
N50L	Nickel Endcap	24	225	Fillet leak at anode end
N51L	Nickel Endcap	27	201	Fillet leak at cathode end
N52L	Nickel Endcap	7	93	Fillet leak at cathode end
K53L	Kovar Endcap, zirconium only	128	1315	Fillet leak at cathode end
K54L	Kovar Endcap, zirconium only	116	1266	Leak in BPCC
K55L	Kovar Endcap, zirconium only	100	600	Not formally tested, used in power supply checkouts
K56L	Kovar Endcap, hybrid seal	14	145	Fillet leak at anode end
K57L	Kovar Endcap, hybrid seal	---	---	Not tested, could not be started
K58L	Kovar Endcap, hybrid seal	15	122	Cathode deactivation, could not be started

Kovar endcap lamps with zirconium-only seals (i.e., brazed with only a zirconium shim between the Kovar and sapphire) exhibited significantly greater lifetimes than first iteration Kovar endcap lamps. In contrast, Kovar lamps with hybrid seals were again short-lived although only one of three failures was seal related.

During second iteration life testing, an ignition problem was encountered in some of the lamps. This problem seemed to be related to the use of the pure tungsten cathodes. The starting problem was experienced in lamps K57L, K58L, N49L, and possibly K55L. If these lamps could be started at all, they ran either with a high voltage, low current "streamer" type of arc drawing current only from the "boost" supply or operated from the primary power supply with a low voltage, high current arc. In both cases, severe cathode overheating and sputtering took place. It was believed that the lack of cathode activation due to the absence of alkali metal on or near the tip surface in these lamps when they were ignited was responsible for these problems. (The alkali metal had perhaps been transported to the anode end of the lamp during the final post-fill 300°C bake.) With sufficient voltage available from either the "boost" or primary power supply, arcs could still be struck successfully but probably developed large cathode fall voltages in order to heat the cathodes to temperatures high enough for adequate electron emission from the high work function unactivated pure tungsten. (This problem had been avoided in previous lamps because their thoriated tungsten cathodes had reasonably low work functions even without alkali metal activation.) Despite the problems encountered with the pure tungsten cathodes, it was believed that the starting problems could have been avoided had a more optimum cathode shape been utilized. For example, with a sharply pointed and heat choked tip, the required high emission temperature could have been generated in a local hot spot rather than throughout the bulk as with the hemispherical tip. (Subsequent success with pointed tungsten cathodes was achieved later in the program. This success was of extreme importance as a solution to the problem of deactivation that developed in later lamps.)

All of the Kovar endcap lamps except K53L were nickel plated for oxidation protection, the plating being applied on the endcaps and over the seal regions. It was clear from the test results that the nickel plate was ineffective, at least in the seal regions, due to poor plating adherence to the zirconium containing braze fillets.

The results of second iteration lamp life tests led to the selection of a single design for the third iteration lamps based on the use of a zirconium-only seal and Kovar endcaps.

C. <u>Third Iteration</u>

1. <u>Design</u>

A Kovar endcap lamp with zirconium seals and 0.38 mm (0.015 in) thick cups was selected for the single third iteration design, shown in Figure 2. The following modifcations were made to the second iteration design:

1. Sapphire of 90° orientation (specifically 90°A, see Appendix A) was used for the envelopes and backup rings. Experiments on the envelope study task, Section IV-A, had shown the 90° material to be significantly more resistant to BPCC (Basal Plane Cleavage Cracking) than the 60° material used in earlier lamps.
2. The overall lamp length was increased by 6.35 mm (0.25 in) at the anode end and a locating pin was added to the cathode end heater mount to comply with life test cavity interfacing requirements imposed at that time.
3. Tungsten containing 2% thoria was used as the cathode material because of the bad experience with pure tungsten in second iteration lamps.
4. The envelopes were cleaned prior to use in various strong acids in accordance with a procedure recommended by Union Carbide. This treatment is believed

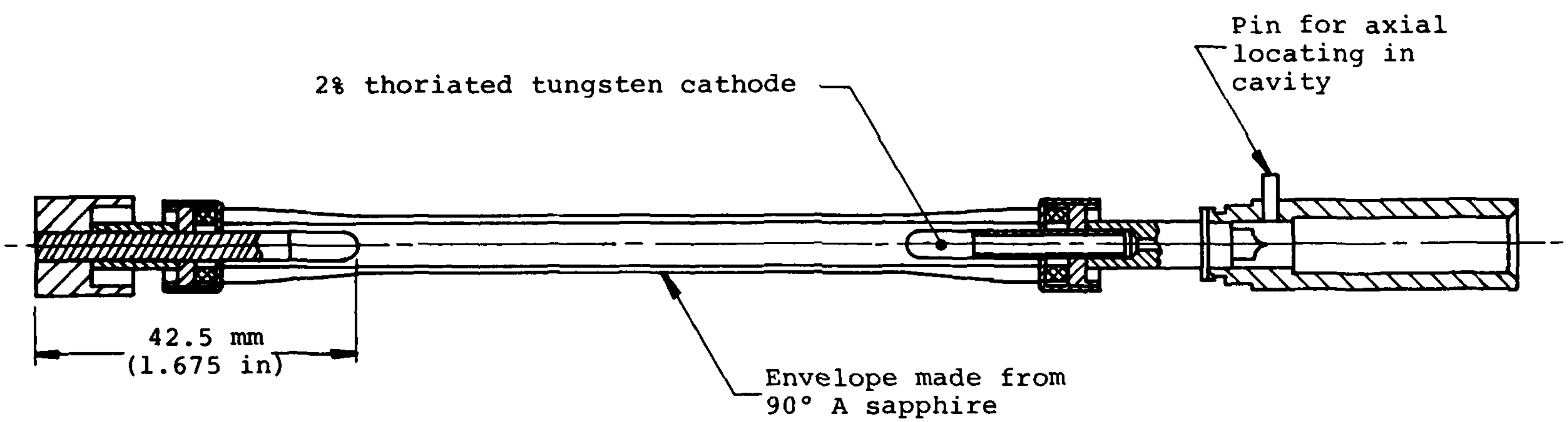


Figure 2. Third Iteration Lamp Design

to remove surface impurities on the sapphire that acetone and methanol, used in earlier cleaning procedures, cannot dissolve.

As before, the endcaps and seals were electroplated with nickel to 0.025 mm (0.001 in) nominal thickness for oxidation protection. The lamps were filled with 75%K-25%Rb and 100 kPa xenon, in accordance with instructions from MDAC-SL.

Two significant problems were encountered in the fabrication of these lamps. First, yield in the machining of the 90° envelopes was poor (approximately 60%) due to cracking on the m-plane ($10\bar{1}0$) during polishing at Insaco. Second, brazing yield on envelope assemblies was poor (approximately 50%) due to inadequate flatness of the seal surface of the Kovar cups.

A photograph of a completed third iteration lamp is shown in Figure 3.

2. <u>Test Results</u>

Ten third iteration lamps were delivered to MDAC-SL for life testing. This testing was carried out using ILC-built, power-regulated, automatically cycled power supplies. The lamps were operated in Sylvania-built life test fixtures that had cylindrical (rather than elliptical) dielectric mirrors to reflect lamp radiation onto the lamp envelope, thereby inducing envelope temperatures anticipated during eventual operation under zero-g conditions. After 500 hours of testing in ambient air, a cover gas of dry nitrogen was used to minimize subsequent oxidation of the lamp endcaps and to simulate the inert atmosphere to be used in the space borne lamp pumped laser.

The results obtained in the life tests of third iteration lamps are shown in Table 3. The average lifetime for the group was 2685 hours discounting two early failures not reflective of the design per se. The two early lamp failures were traceable to errors in fabrication. In lamp K65S, excessive stock removal

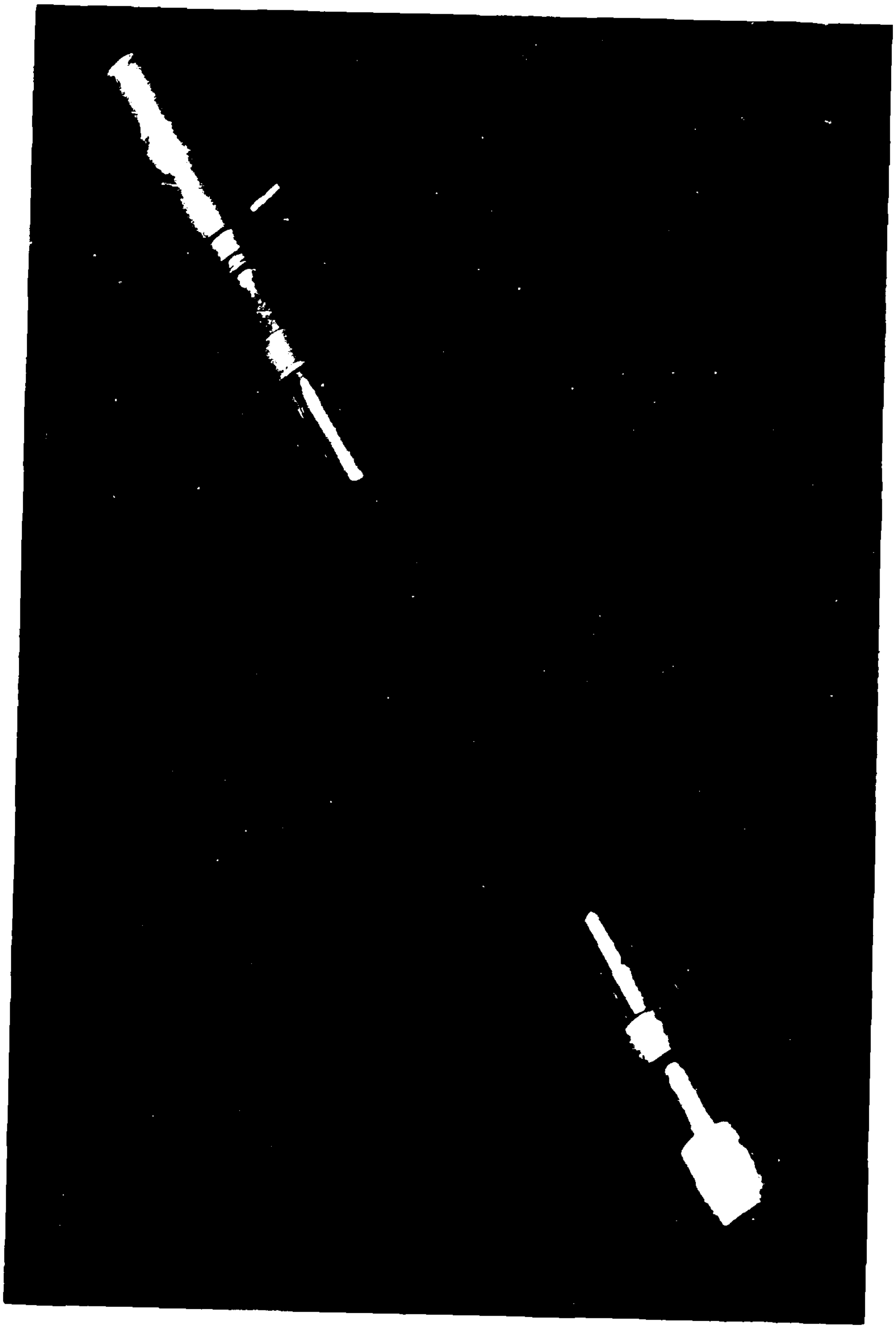


Figure 3. Third Iteration Lamp

during hand grinding of the Kovar seal cup to produce adequate flatness for brazing resulted in a very short path length for intergranular oxidation failure. In lamp K80S, a nickel adapter cap had inadvertently been used at the cathode end. The resulting mismatched weldment to the Kovar seal cup failed by stress-enhanced intergranular oxidation. This failure mode had been encountered in earlier work.

TABLE 3

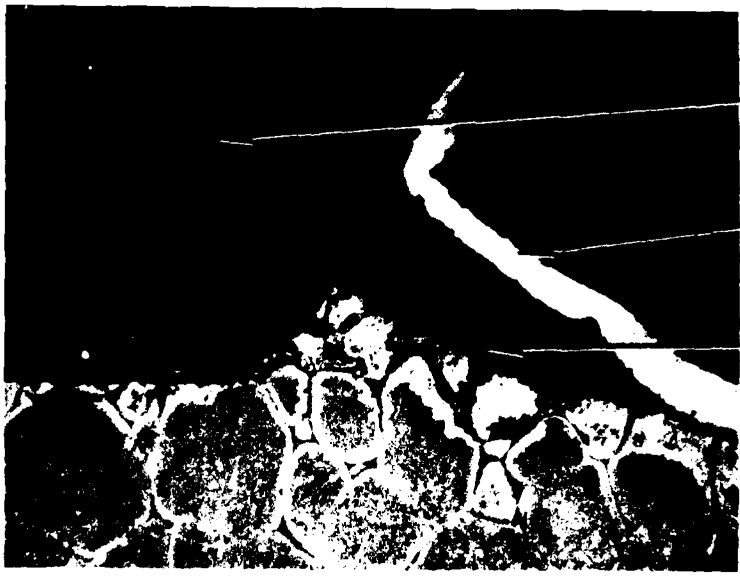
THIRD ITERATION LAMP LIFE TEST RESULTS

Lamp Number	Lifetime Cycles	Hours	Failure Mode
K65S	28	312	Fillet leak at cathode end
K66S	169	1610	Fillet leak at cathode end
K69S	100	1303	Fillet leak at cathode end
K73S	444	5250	Testing terminated
K75S	---	----	Not life tested. Control lamp for fluorescent and laser tests
K77S	200	2160	Fillet leak at cathode end
K78S	170	1800	Fillet leak at cathode end
K80S	33	255	Weldment leak at cathode end
K84S	400	5471	Testing terminated
K85S	123	1200	Fillet leak at cathode end

All other failures were due to endcap leakage at the braze fillets caused by intergranular oxidation in the Kovar cups. The photomicrograph in Figure 4 depicts such a failure site in lamp K69S. The poor adherence of the nickel plate in the seal region and the consequent lack of oxidation protection is indicated in the photomicrograph.

During the life testing lamps were periodically evaluated for pumping efficiency using a fluorescence output test that

(a) Actual leak site, approximately 200X



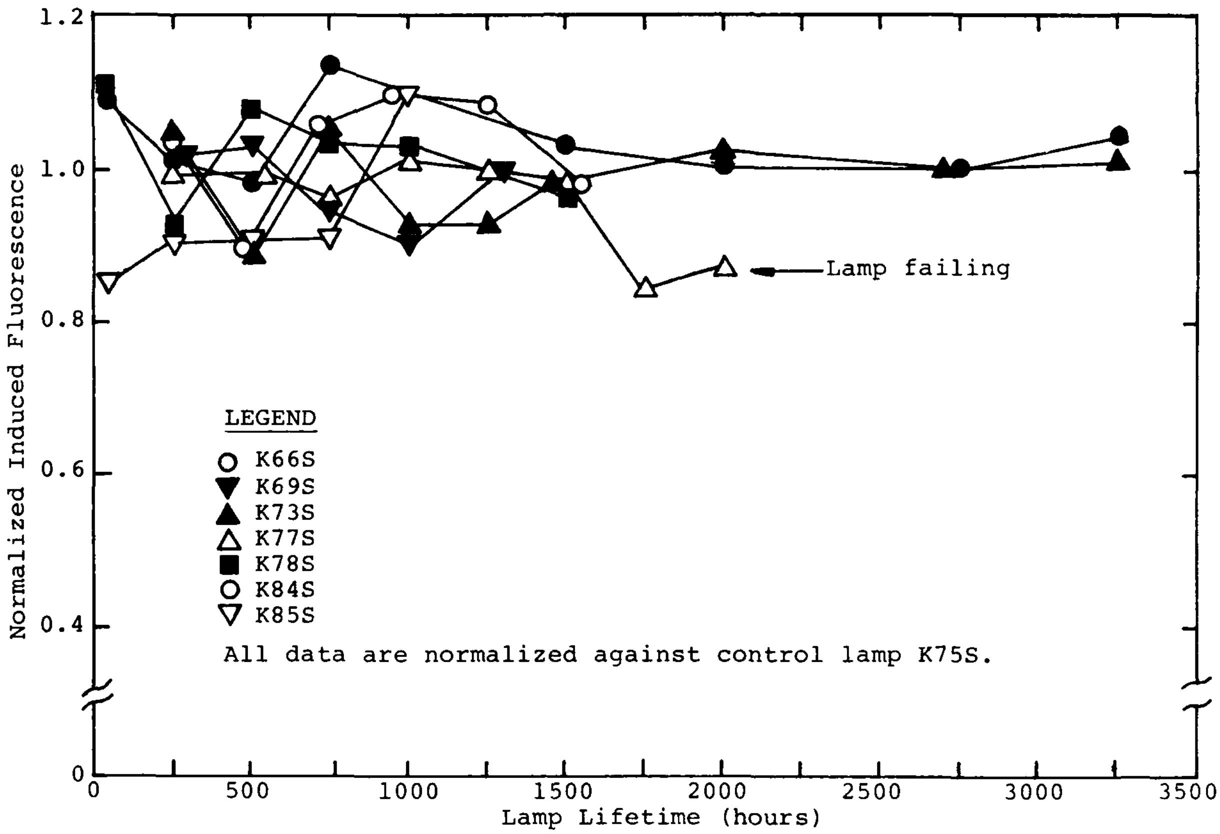
(b) Opposite side of seal showing ineffectiveness of nickel plate, approximately 200X

Figure 4. Photomicrographs of Leak Site, Lamp K69S

involved measuring the relative levels of 1.06 μm fluorescent radiation induced in a Nd:YAG rod by the lamps and, less often and on only four lamps, a laser performance test (described in Section IV-B). One lamp from the life test group, K75S, was used as a control for these tests. Results of fluorescence and laser tests, normalized against values for lamp K75S, are given in Figure 5. Despite a good deal of experimental scatter, the curves indicate that lamp output remains stable throughout life.

Two other problems were experienced with third iteration lamps. Due to a poor thermal design match between the lamp and the life test fixtures, temperatures at the anode ends of the lamps were too low, causing gradual transport of alkali metal to that end from the intended temperature-controlled reservoir at the cathode end. As testing proceeded, auxiliary heater power in several lamps had to be gradually increased from an initial level of 10-20 watts to a full power level of 50 watts in order to sustain the desired 69 volt lamp operating voltage. Later in the testing period, the heater power for most lamps had to be reduced (in some cases to zero) because of the cathode deactivation discussed below.

Seemingly concurrent with the "anode cold spotting" effect was the problem of cathode deactivation. At the onset of this phenomenon, arc attachment to the thoriated cathode shifted to an area on the side of the cathode rather than at the tip. In extreme cases, the cathodes became discernibly incandescent and evaporated material onto the adjacent envelope walls. It was hypothesized that the deactivation was caused by "poisoning" of the cathode surface, perhaps by free metallic thorium, causing a reduced "sticking coefficient" of potassium and rubidium atoms and a consequent increase in cathode work function. It was not clear at the time whether such cathode deterioration was an inherent characteristic of thoriated tungsten material in this application or was the result of reduced K-Rb vapor pressure resulting from the anode end cold spotting discussed above. A side effect of the cathode deactivation effect was that the overheated cathode caused reservoir temperature to also increase, thus reducing heater power requirements.



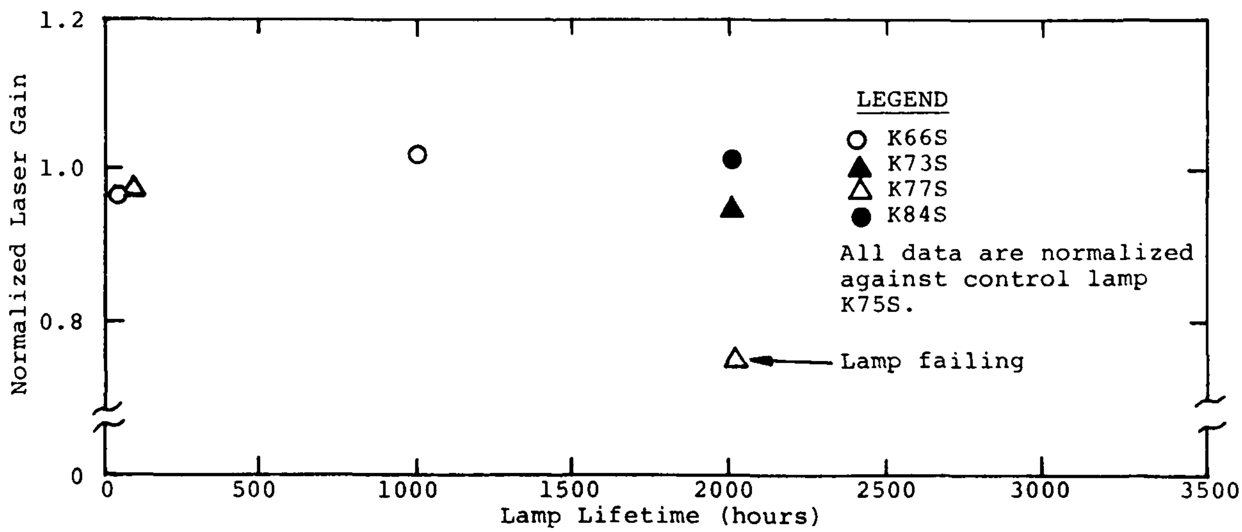


Figure 5. Fluorescent and Laser Test Results for Third Iteration Lamps During Life Testing

At least one lamp, K66S, from the third iteration group had basal plane cracks in the envelope despite the use of the 90° sapphire. However, the cracks were very small and became discernible only after a thousand hours or more of lamp operation.

D. Fourth Iteration

1. Design

Fourth iteration lamps (Figure 6) were built immediately after completion of the third iteration lamps and were life tested at ILC while third iteration lamps were under test at MDAC-SL. These lamps embodied several design and processing features of interest that were not included in the third iteration lamp design, including:

1. Use of other envelope orientations, 0° and 90°M, that had exhibited good BPCC resistance in the envelope study task.
2. Use of a thicker wall envelope (1.25 mm vs. 0.75 mm for standard envelopes) with a larger outside diameter (7.5 mm) in some of the lamps to evaluate the benefits, if any, of lower temperatures on the internal surface that result from more efficient heat dissipation by the larger external surface area.
3. Use of a vitreous (glaze) coating fired onto the seals and endcaps for oxidation protection.
4. Use of heat choked, flat tip anodes designed to isolate anode overheating caused by lamp operation in the "xenon" mode (see Section V-B) from the nickel stem and to possibly increase lamp efficiency by virtue of their shape.
5. Use of pointed, 2% thoriated tungsten cathodes, postulated to be more efficient than the normal hemispherical type (see Section IV-C).

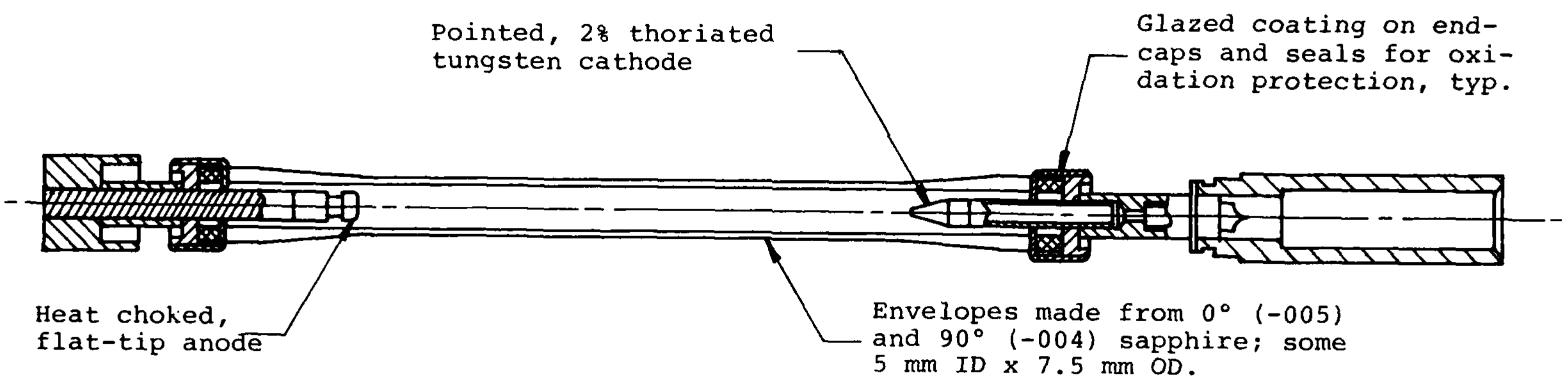


Figure 6. Fourth Iteration Lamp Design

6. Use of a modified electrode cleaning procedure involving immersions in HCl and NaOH (the earlier procedure involved only acetone and methanol degreasing).

The brazed end seals were of the same design as in third iteration lamps. Fourth iteration lamps were filled with the baseline 75%K-25%Rb and 100 kPa xenon.

The fabrication procedure for these lamps was modified to accommodate the elevated temperature glaze firing operation. The lamps were built with extra long fill appendages. After the normal 600°C vacuum bake out, the lamps were pinched off empty in the glove box, glazed, and then returned to the glove box where the initial appendages were cut off to the normal length to allow subsequent filling, lamp closing, and final assembly steps in the conventional manner.

The glaze used was Owens Illinois Article 1338 (see Section IV-E). The starting glass powder was mixed with a nitrocellulose amylacetate vehicle to produce a workable slurry and applied to desired surfaces using a spatula. Firing was carried out at 800°C with a slow (approximately 5°C per minute) heat up rate. The resulting vitreous coatings were not without faults, particularly areas of incomplete glass coverage over the cup/cap weldments and on the adapter cap itself.

2. Test Results

Ten fourth iteration lamps were completed, nine of which were life tested at ILC. ILC-built, autoramping, current-regulated power supplies and simple, tubular, fused quartz lamp holders were used for the testing. An ambient air atmosphere prevailed throughout the testing. (One lamp, K93L, was tested for 550 hours at ILC and then transferred to MDAC-SL for continuation of testing in a dry nitrogen cover gas.)

The lamp test matrix and test results are presented in Table 4. The average lifetime for the group was 2877 hours discounting lamp K102L which was pulled from testing after only 250 hours in order for large cleavage cracks in its envelope to be studied. The most significant test result was that no failures occurred by leaks in the brazed seal fillets. This attests to the effectiveness of the vitreous coating in protecting the underlying metal from oxidation. Surprisingly, the glaze coatings developed cracks and seemed devitrified on many of the lamps, especially at the cathode end where temperatures were higher, and yet remained protective.

TABLE 4

FOURTH ITERATION LAMP LIFE TEST RESULTS

Lamp Number	Envelope Orientation	Envelope Size ID X OD	Envelope Cleaning Agent	Lifetime Cycles	Lifetime Hours	Failure Mode
K91L	90°M	5x6.5 mm	solvent	141	4368	Weldment leak at cathode end
K92L	90°M	5x6.5 mm	solvent	29	493	Weldment leak at cathode end
K93L	90°M	5x6.5 mm	solvent	271	5441	Testing terminated
K101L	0°	5x6.5 mm	acid	56	590	Weldment leak at cathode end
K102L	0°	5x6.5 mm	acid	21	251	Testing discontinued, large BPCC
K103L	0°	5x6.5 mm	acid	208	5303	Testing terminated has BPCC, envelope very discolored from onset
K104L	90°M	5x7.5 mm	acid	66	991	Weldment leak at cathode end
K105L	90°M	5x7.5 mm	acid	141	4467	Testing terminated
K106L	90°M	5x7.5 mm	acid	55	1364	Pinch-off leak

The predominant failure mode was weldment leaks in the endcaps. Failure analysis on several failed lamps indicated that excessive oxidation of the Kovar had occurred during the glazing operation. In areas where glass coverage was inadequate the degree of oxidation was severe (Figure 7). In these cases, additional oxidation apparently occurred during lamp operation until intergranular oxide stringers reached the inside of the lamp. Alkali metal attack of the metal oxide then caused relatively rapid failure.

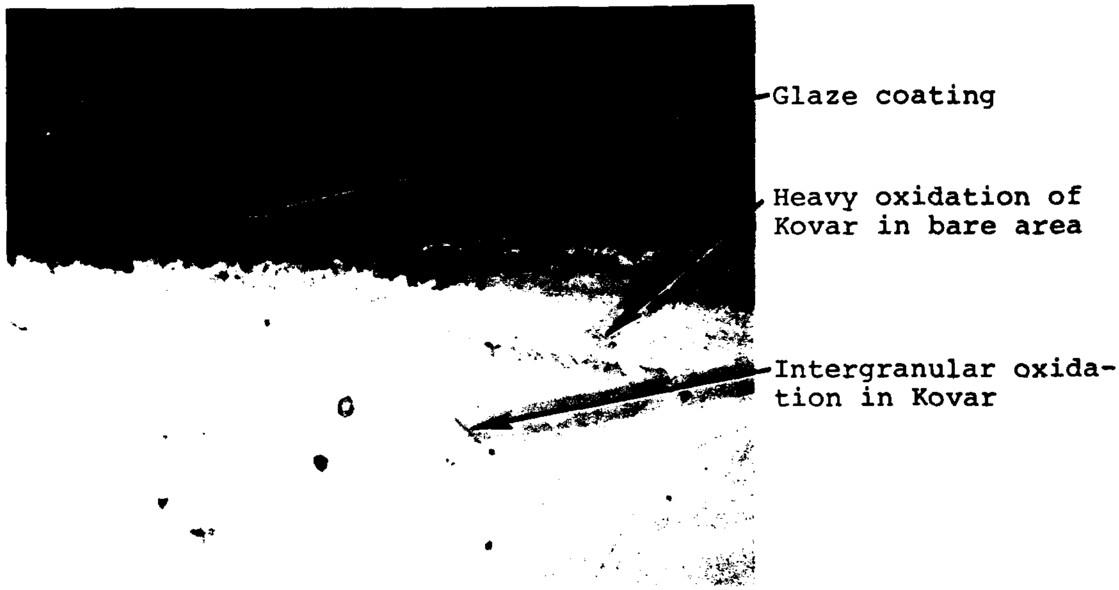
It is believed that unnecessarily high glaze firing temperatures and long firing schedules were in large part responsible for the process-induced oxidation. Also, the need for more complete glaze coverage was obvious.

Cathode deactivation occurred in virtually all fourth iteration lamps and after fewer operating hours than had been experienced with third iteration lamps. The pointed geometry of the fourth iteration cathodes possibly caused this faster deterioration. Some lamps seemed to temporarily recover from this phenomenon after 100 to 200 hours of operation and subsequently ran normally for many hundreds of hours.

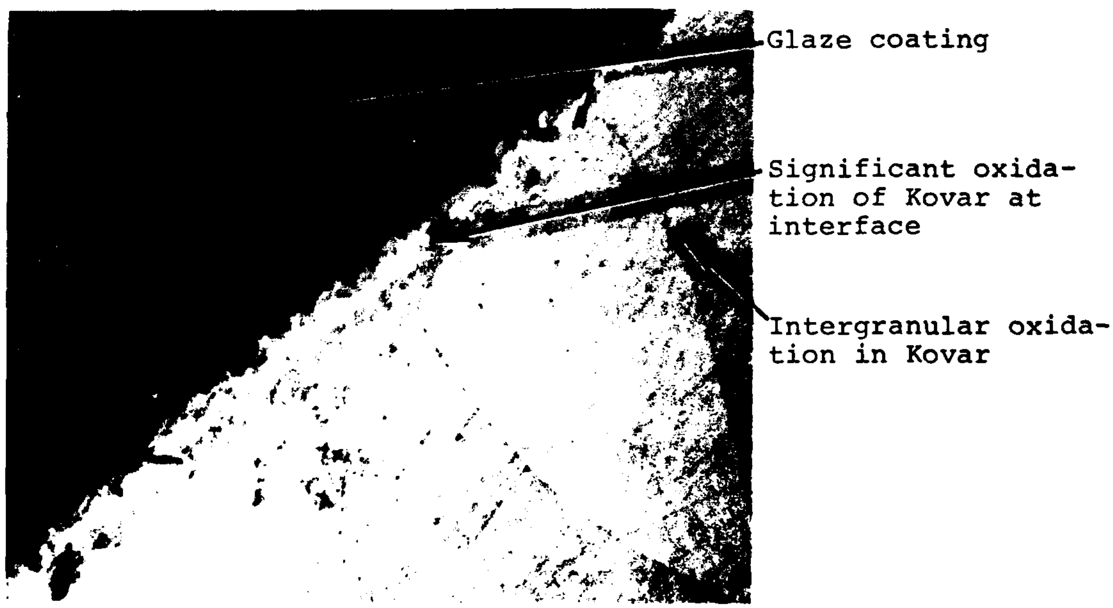
Sapphire envelopes of 0° orientation did not exhibit the expected immunity to basal plane cracking. For example, cracks in lamp K102L became very pronounced in 250 hours. Although, as noted, testing was terminated with this lamp still intact in order to preserve the cracked envelope for possible later examination by scanning electron microscopy, it is likely that envelope failure would have occurred in the next one hundred hours of operation.

Some 90° envelopes also exhibited basal cracking. The cracks generally grew to a terminal depth less than the thickness of the envelope wall within 2000 hours of lamp operation.

There was no apparent advantage, either in resistance to basal cracking or frosting with the thicker wall lamps, K104L, K105L, and K106L.



(a) Glazed and bare areas, approximately 200X



(b) Glazed area showing effect of process-induced oxidation, approximately 400X

Figure 7. Photomicrographs of Kovar Oxidation in Glaze-Coated Weldment Region

No differences in lamp appearance attributable to the cathode cleaning treatments were discernible. However, deposition of cathode material on the envelope due to cathode deactivation may have obliterated any such effects.

Finally, the pinch-off failure in lamp K106L was of concern, not because this mode of failure was common (on the contrary) but because the cause was unclear. All pinch-offs were backwelded and appeared sound before lamp operation.

E. Fifth Iteration

1. Design

The fifth iteration design (Figure 8) was similar to third and fourth iteration designs, combining the vitreous overcoat for oxidation protection of the brazed end seals as employed successfully on fourth iteration lamps with a 90°A sapphire envelope and a standard hemispherical tip, thoriated tungsten cathode as used in the third iteration design (a solution to the cathode deactivation problem had not yet been demonstrated). The anode mounting base was reduced to 6.35 mm diameter and shortened to 108.08 mm (measured from the cathode tip). The baseline lamp fill remained unchanged, i.e., 75%K-25%Rb and 100 kPa xenon. Five of the fifth iteration lamps delivered to MDAC for life testing were filled with 100%K, however.

The procedure for applying the vitreous overcoat was upgraded from that used previously to include a controlled preoxidation firing cycle (for maximum bond strength between the glass coating and the metal endcap substrate) and a much shorter overcoat firing cycle to prevent excessive additional oxidation of the underlying metal. Also the lamps were filled and closed off prior to these steps, unlike fourth iteration lamps which were closed off empty and reopened after overcoating for filling and final closure.

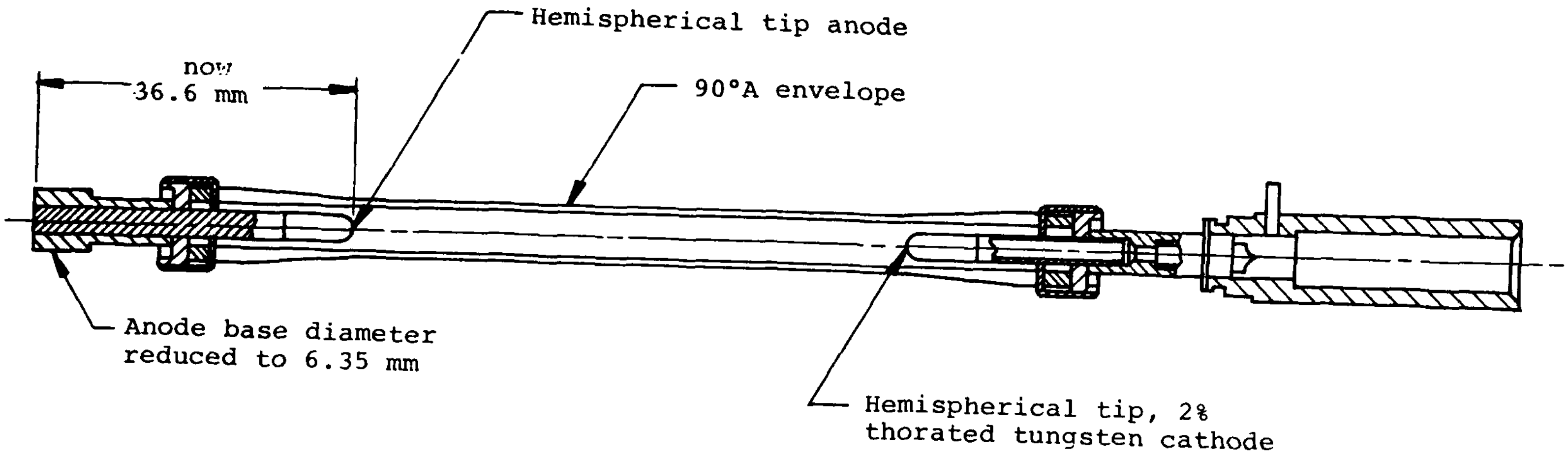


Figure 8. Fifth Iteration Lamp Design

2. Test Results

Thirty-four fabrication starts were made on fifth iteration lamps to produce 31 initially operable lamps (91 percent yield).

The first three envelope assemblies, brazed with zirconium of 0.017 mm thickness, had poor interfacial wetting and could not be used. All subsequent assemblies were brazed with 0.021 mm thick Zr, resulting in a 100 percent yield. Use of 0.021 mm Zr has continued since that time.

Two lamps failed during burn-in due to pinch-off leakage, apparently caused by contamination of the pinch-off weldment with alkali metal residue from the filling operation. In both cases the fill was 75%K-25%Rb.

The major problem encountered during burn-in (and, as it turned out, during subsequent life testing) was cathode deactivation. As noted earlier, this effect is believed to be caused by a change in the nature of the thoriated tungsten surface such that the thin film of alkali metal condensate which ordinarily resides on the surface and provides a low thermionic work function is displaced. More specifically, it is hypothesized that chemical reduction of ThO_2 in the cathode and resulting coverage of the surface with metallic thorium prevents a stable alkali metal film from forming. The significantly higher work function of the thorium film and consequent higher temperature required to produce the electron emission necessary to sustain the arc explains the observed incandenscense. Five lamps exhibited cathode deactivation effects during burn-in and were rejected.

Formal acceptance testing was performed for the first time in the SFTS program. The acceptance tests included a functional test to demonstrate the ability of the lamp to ignite properly and reach a full power, full voltage operational state within 20 minutes, a fluorescent output measurement (0.5 μW required at minimum), and a spectral irradiance scan. Some difficulties were encountered in passing the functional test, primarily because the relatively low starting current and modest current ramp rate used at that time did not allow the lamps to reach steady state operating temperatures safely prior to the 20 minute limit.

A careful visual inspection and measurement of the electrical resistance of the vitreous endcap overcoats were also included in the acceptance tests. Visual and electrical defects were found in most of the lamp coatings although less so in later lamps in the group (reflecting steadily improving overcoat application and firing techniques). The visual observations, supplemented by resistance measurements, served as the primary criterion for a priori predictions of the relative expected lifetimes of the 15 fifth iteration lamps delivered to MDAC for life testing.

The lamps fell into four projected lifetime groups as shown in Table 5, which compares predictions with actual life test results. Good correspondence between predictions and test results was obtained.

Detailed results of fifth iteration life tests are shown in Table 6. The group average lifetime was 5077 hours with five of the fourteen lamps still operable when this report was written. (One lamp, S/N 140-5, was used for a fluorescent output test standard and not life tested.)

The main structural failure mode encountered was oxidation-induced weldment leakage. The last several lamps fabricated, i.e., S/N's 155 through 162, had better oxidation protection glaze coatings than earlier lamps, explaining their better survivability.

Virtually all of the life tested lamps exhibited severe cathode deactivation with attendant cathode end overheating (which almost certainly accelerated the weldment oxidation process) and heavy deposition of cathode tip material on the adjacent envelope wall. Because of the heavy deposits and the inherently wasteful heating of the cathode by the arc, fluorescent output values for the lamp were significantly below the 0.5 μW specification minimum throughout the life tests. The deposits and high cathode temperature probably caused the envelope fracture (adjacent to the cathode) in lamp 162.

There was no evidence that the 100% potassium fill was detrimental to lamp performance or lifetime. This result was

TABLE 5

PREDICTED AND ACTUAL LIFETIMES FOR FIFTH ITERATION LAMPS

Group	Lamp Nos.	Predicted Lamp Lifetimes	Predicted Failure Mode	Actual Lamp Lifetimes	Actual Failure Mode	Actual Average Lifetime for Group
A	133-5	< 1000 hrs	Pinch-off leak	3000 hrs	Weldment leak	2842
	139-5			2683	Weldment leak	
B	141-5	1000 hrs min., probably > 2000 hrs	Weldment leak	1877	Weldment leak	4209+
	147-5			4660	Weldment leak	
	149-5			613	Weldment leak	
	134-5			2950	Weldment leak	
	137-5			8179*	-	
	156-5			6975*	-	
C	155-5	> 3000 hrs	Weldment leak	7747*	-	7121+
	140-5			Not tested	-	
	142-5			6495	Weldment leak	
D	160-5	Very long	?	7550*	-	6476+
	161-5			7535*	-	
	162-5			5308	Envelope fracture	
	143-5			5511	Weldment leak	

*Denotes lamps still on life test.

TABLE 6

FIFTH ITERATION LAMP LIFE TEST RESULTS

Lamp Number	Lifetime Cycles	Lifetime Hours	Failure Mode
133-5	170	3000	Cathode end weldment leak
134-5	120	2950	Cathode end weldment leak
137-5	(313)	(8179)	(Still operable)
139-5	113	2683	Cathode end weldment leak
141-5	99	1877	Cathode end weldment leak
142-5	217	6495	Cathode end weldment leak
143-5	199	5511	Cathode end weldment leak
147-5*	125	4660	Cathode end weldment leak
149-5*	82	613	Cathode end weldment leak
155-5	(286)	(7747)	(Still operable)
156-5	(364)	(6975)	(Still operable)
160-5*	(229)	(7550)	(Still operable)
161-5*	(254)	(7535)	(Still operable)
162-5*	220	5308	Envelope fracture

*Denotes lamps with 100%K fill; all others 75%K-25%Rb.

significant in justifying a change to the more efficient potassium fill in sixth iteration lamps.

F. Sixth Iteration

1. Design

The sixth iteration lamp (Figure 9) was the final design developed on the program. As such it incorporated a number of design modifications intended to correct deficiencies in the fifth iteration lamps and/or for proper interfacing with the final version of the laser cavity. These included the following:

1. The cartridge heater previously used for control of the alkali metal reservoir temperature at the cathode end of the lamp was replaced by a coiled, sheathed heater located immediately around the reservoir area; this modification was made to improve heater efficiency and lamp voltage control response time.
2. Pointed, pure tungsten cathodes replaced the previously used hemispherical tip thoriated tungsten cathodes; separate studies (see Section IV-C) had shown the new cathodes to be immune from the deactivation problem and also from the peculiar ignition problems exhibited by pure tungsten cathodes in second iteration lamps.
3. A "hybrid" oxidation protection coating (see Section IV-E) was used combining the vitreous overcoat for protection of the brazed seals with nickel electroplating for weldment protection; this modification was made to solve the problem of weldment leakage exhibited by all failed fifth iteration lamps. (Because the "hybrid" coating had not been proven out in any long term tests prior to its adoption for sixth iteration lamps several sixth

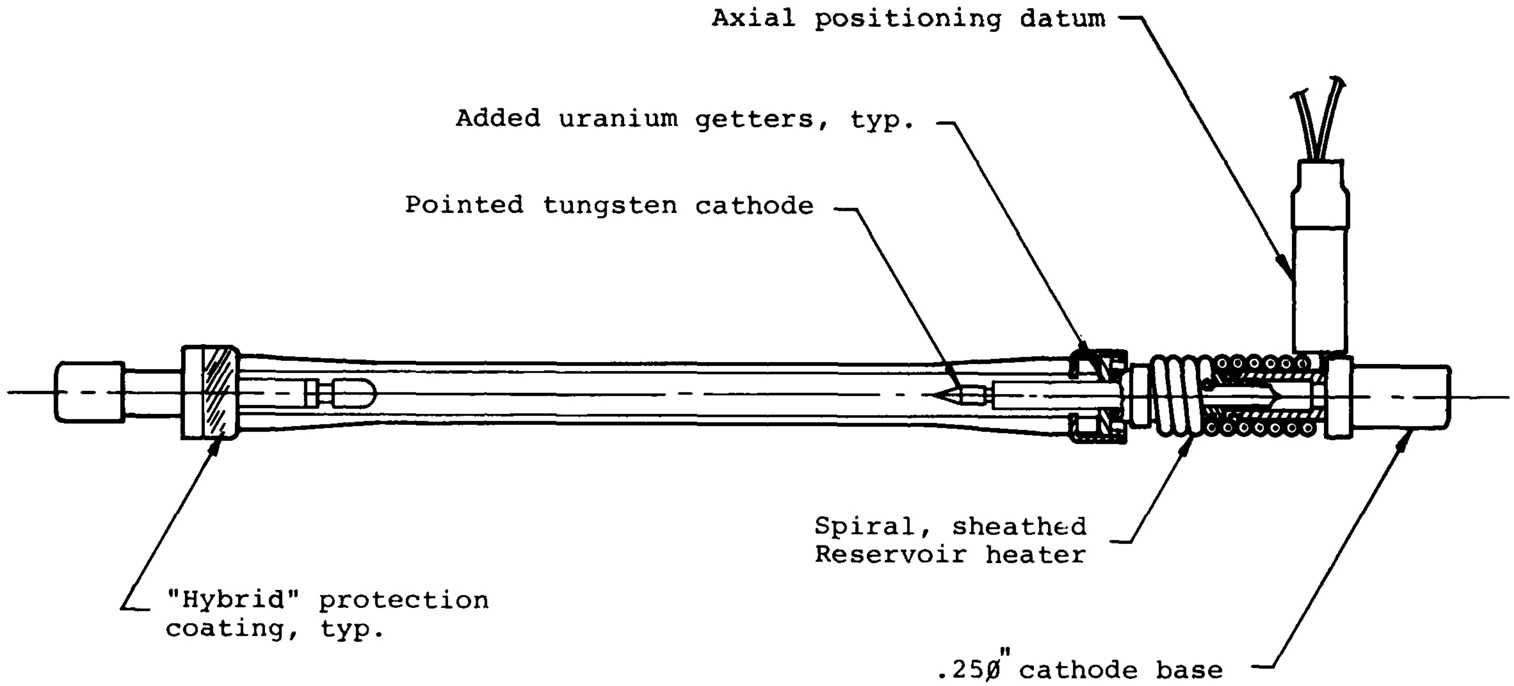


Figure 9. Sixth Iteration Lamp Design

iteration lamps were also fabricated as part of the Filling Procedure Optimization task, Section IV-I, with the Kovar endcaps protected entirely with the vitreous overcoat as a back-up design in case of long term problems with the hybrid coating. These lamps were intended to be life tested in parallel with the baseline sixth iteration lamps described in this section.)

4. The alkali metal fill was changed from 75%K-25%Rb to 100% potassium; this modification was made to improve laser pumping efficiency (see Section IV-B) and to eliminate the need for premixing of the alkali metals, which increases the possibility of oxygen contamination.
5. The cathode mounting base was reduced to 6.35 mm diameter and shortened by 8.1 mm.
6. The heater lead transition section and its slip fit ceramic insulator sleeve were adopted as the new datum for axial positioning of the lamp in the laser pump cavity.
7. Depleted uranium washers were sandwiched between the back-up rings and adapter caps at each end of the lamp to getter oxygen that possibly permeates slowly into the lamp through the thin walled Kovar cups.

Prior to fabrication of five sixth iteration lamps for life testing at MDAC and several additional lamps for use in laser experiments, a number of prototype lamps were constructed for preliminary check-out of the thermal design (Section IV-G) and for use in experiments to evaluate improved lamp operating procedures (Section IV-H). These lamps were made prior to adoption of the 100% potassium fill. Consequently, some had 75%K-25%Rb fills.

2. Test Results

The five sixth iteration life test lamps were subjected to formal acceptance tests prior to delivery to MDAC-SL. Included in these tests was an irradiance measurement that had been substituted for the previously used fluorescent output test because of its more direct, reliable calibration. Normal irradiance of lamps in the combined wavelength bands of 730 to 770 nm and 790 to 830 nm (corresponding with principal excitation bands in Nd:YAG) was required to exceed 4.0 W/sr. All of the lamps easily satisfied this requirement (Table 7) and, owing to a new operating procedure that powered the lamps up more quickly, also easily reached their nominal operating voltage (72 $\pm$ 2 V) within 20 minutes in functional tests. The functional tests were performed using a laser cavity furnished by GTE-Sylvania, informally termed the "98 percent" cavity because of its close simulation of the final laser cavity design. Heater power required to sustain a lamp voltage of 72 V was found to be in excess of the 25 W allowed indicating that the thermal design match between the lamp and cavity was not optimized. Earlier thermal design check out of a prototype sixth iteration lamp in the "98 percent" cavity had not revealed this problem, probably because that lamp had been filled with 75%K-25%Rb which has a slightly higher total vapor pressure than 100% potassium.

The lamps were then subjected to vibration tests (see Section IV-J) followed by a second round of functional tests to confirm that the lamps had not been damaged by the vibration environment. During these functional tests a second symptom of the thermal design mismatch between the lamp and cavity became apparent. Three of the five lamps exhibited voltage fall-off after 2-3 hours of operation. Lamp voltages settled at 66-67 V and would not respond to heater power increases up to 40 W. Voltage could be reduced to values below 66 V by reducing heater power to 20 W or less, however. Increasing lamp input power to 300 W (thus raising

TABLE 7

SIXTH ITERATION LAMP ACCEPTANCE TEST RESULTS

Lamp No.	"Useful" Irradiance (W/sr)	Previbration Functional Test			Post Vibration Functional Test			Remarks
		Pulses to Ignite	Stability Test	Heater Power	Pulses to Ignite	Stability Test	Heater Power	
194-6	4.74	1	ok	27.0 W	1	ok	30.0 W	-
198-6	4.53	1	ok	35.6 W	1	Rej. (see remarks)	34.7 W	Voltage fell to 66 V near *end of stability cycle due* to anode end cold spotting
203-6	4.40	1	ok	34.1 W	1	ok (see remarks)	31.2 W	Voltage falling at end of stability test
204-6	4.39	1	ok	29.8 W	1	Rej. (see remarks)	33.0 W	Voltage fell to 66 V during prestability test conditioning cycle
205-6	4.61	1	ok	34.4 W	1	ok	32.3 W	-

anode end temperatures) caused the lamp voltage to rapidly climb back into the 70 V range where, with appropriate adjustment of heater power, it could be controlled at 72 V. These observations strongly suggested that the original voltage fall-off was caused by "anode end cold spotting", i.e., gradual transfer of the potassium from the cathode to anode end of the lamp due to lower temperatures there, with attendant loss of lamp voltage controllability. Again the change to a 100% potassium fill probably explains the fact that this effect was not encountered in earlier thermal design proof tests. Rectification of this problem will be attempted by modification of the laser cavity design; no changes to the lamp thermal design will be made.

SECTION IV

LAMP TECHNOLOGY DEVELOPMENT

As noted earlier, the subject Air Force-funded SFTS program served primarily as a vehicle for development of lamp technology to support the iterative design development work on the concurrent MDAC subcontract. Several critical technology development tasks were successfully completed. These are described in detail below.

A. Envelope Technology

This task, the most extensive engineering support task in the program, addressed technical problems associated with the sapphire lamp envelopes, in particular basal plane cleavage cracking and, to a lesser extent, potassium aluminate crystallite growth on the internal walls (so-called "frosting").

1. Basal Plane Cleavage Cracking

Work on the cleavage cracking problem included concurrent efforts to develop a plausible working hypothesis for explaining the cracking and to experimentally evaluate various design and processing modifications for their effectiveness in counteracting the cracking. At least two of these modifications appeared to be beneficial and were incorporated in third iteration lamps where their effectiveness in curbing cleavage cracking was confirmed.

a. Hypothesis for Cleavage Cracking

Based on findings from scanning electron microscopy (SEM), energy dispersive analysis by x-ray (EDAX), and x-ray diffraction (XRD) studies on envelopes with basal cracks and a thorough survey of literature on fracture of sapphire, a plausible hypothesis was developed to explain cleavage cracking.

SEM examination of interior surfaces of cracked envelopes from EFM-phase lamps revealed either open abysses (Figure 10) or a second phase material within crack sites (Figure 11). Also found on interior walls were second phase crystallites aligned with the sapphire basal plane but not associated with cracks. EDAX analysis of the material within cracks and the surface crystallites showed both to contain aluminum and potassium as principal elemental constituents. A sufficient sampling of the surface material was obtained to permit compound identification by XRD. The surface crystallites were determined to be a potassium beta alumina isomorph, $K_2O \cdot 12Al_2O_3$. SEM examination of basal crack surfaces on envelopes that had actually parted into two pieces (Figure 12) showed the presence of ridges and patches of second phase material which were found by EDAX analysis to contain aluminum, potassium, and, frequently, impurities such as iron and silicon.

A survey of the literature indicated that basal plane fracture of sapphire is unusual because of the high fracture energy of the plane in comparison with other low index planes(7). Basal plane mirrors are occasionally found on fracture surfaces of sapphire specimens subjected to high temperature stress-rupture and creep rupture tests(8,9). In such cases the mirrors are located in the region of the apparent crack nucleation site and extend only part way across the fracture surface, the balance exhibiting a "hackled" topography associated with branching of the basal crack onto the other crystal planes. Disagreement exists regarding the mechanisms that cause the partially basal plane cracking. Both rapid crack growth along weak basal twin boundaries and slow crack growth induced by a high temperature evaporation-condensation mechanism have been proposed(10,11).

These proposed mechanisms for basal cracking seem not to apply well to the lamp envelope case. First, large twins have never been found in lamp envelopes, either before or after basal cracking, thus discounting twin boundary fracture as a cracking mechanism. Microscopic near-surface twins induced by grinding or polishing may exist, but they would not account for the complete transwall basal fracture. Also the very slow crack growth observed in lamps is inconsistent with the catastrophic nature of twin boundary fracture reported in the literature. Second, envelope

Figure 10. Scanning Electron Micrograph of Basal Plane Crack (1400X)

Figure 11. Scanning Electron Micrograph of Possible Basal Crack Nucleation Site (2000X)

Figure 12. Scanning Electron Micrograph of Basal Plane Crack Surface (100X)

Figure 10

Figure 11

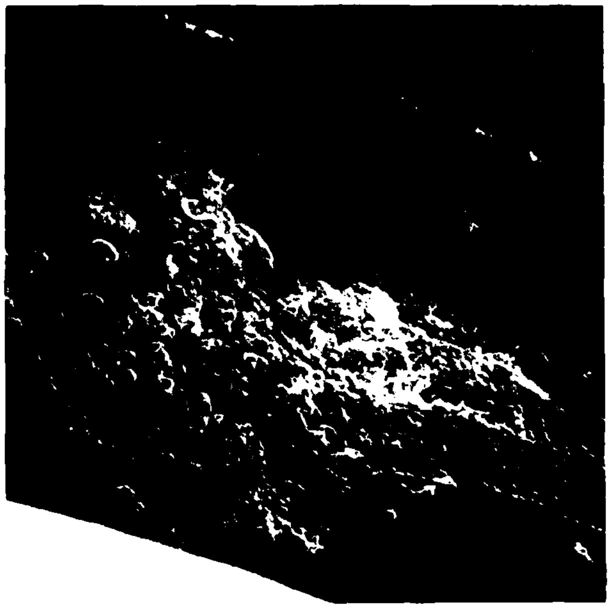


Figure 12

temperatures are no higher than 1100-1200°C, too low for an evaporation-condensation crack growth mechanism to be active. Third, and perhaps most significant, calculations based on conventional models[12,13] show that thermal stresses in the envelope wall arising from radial and axial temperature gradients are modest and, more importantly, compressive on the inside surface where basal cracks nucleate. Thus cracking would not provide thermal strain relief.

The hypothesis developed to explain basal cracking in lamps discounts thermal stress as a root cause of cracking and instead attributes the cracking to a chemical reaction. Specifically it is proposed that the cracks are caused by the epitaxial growth of microplatelets of potassium beta alumina into the sapphire along basal planes. The volume expansion associated with the formation of these platelets generates "wedging" stresses that promote parting of the planes. Formation of the potassium beta alumina is believed to occur by the reaction

$$2K + \tfrac{1}{2}O_2 + 12Al_2O_3 \rightarrow K_2O \cdot 12Al_2O_3$$

where the oxygen reactant is a residual impurity in the original alkali metal fill or (more probably) permeates into the lamp through the metal endcaps or end seals.

Subsequent findings on the program showed a definite correlation between propensity for basal cracking to occur and various chemical variables, thus tending to support this hypothesis.

A description of the envelope cracking problem and hypothesis has been published in the open literature[14].

b. Experimental Work

In the experimental phase of the work on cleavage cracking, a series of lamp design and processing changes were evaluated as possible solutions to the problem. Lamps embodying the experimental changes were life tested in vacuum. Testing in vacuum was employed to provide thermal simulation of zero-g effects (absence of free convection cooling) such as would prevail in a satellite and to possibly accelerate cracking and thereby expedite the evaluation process. (The likely effect of reduced oxygen level exterior to the lamp was not appreciated at the time. The reaction $6K + 37Al_2O_3 \rightarrow 3(K_2O \cdot 12Al_2O_3) + 2Al$ which required no oxygen reactant was assumed to be the dominant crack-causing reaction.) The following modifications were evaluated:

1. Use of 90° and 0° sapphire orientations instead of the standard 60° orientation (sapphire orientation nomenclature is given in Appendix A).
2. Use of a 100% rubidium fill based on the belief that potassium being more reactive than rubidium was alone responsible for chemical reactions that caused cracking.
3. Use of a more aggressive envelope cleaning procedure involving strong acids instead of organic solvents in order to remove impurities that possibly contributed to crack-causing reactions.
4. Use of increased envelope wall thickness (as in some fourth iteration lamps) to reduce the bore surface temperature, thus perhaps reducing the reaction rate.
5. Use of hydrogen gas polishing of the envelope to smooth the envelope bore surface, thus eliminating flaws that might serve as crack nucleation or reaction sites.
6. Use of high temperature annealing in inert gas to nullify residual stress from envelope machining.

The experimental matrix and life test results are given in Table 8. Only the sapphire orientation change to 0° or 90° provided encouraging results. Indeed, the total absence of cracks in

TABLE 8

ENVELOPE TECHNOLOGY TASK LAMP TEST MATRIX AND RESULTS

Lamp Number	Envelope Orien-tation	Envelope Size ID x OD	Alkali Fill K-Rb	Special Envelope Processing	How Tested	Results
N12E	60°	5x6.5 mm	90-10	None	In vacuum for 665 hours	Small BPCC, discernible at 50 hours
N14E	60°N	5x6.5 mm	90-10	None	In vacuum for 694 hours	Medium BPCC, discernible at 50 hours
N15E	60°N	5x6.5 mm	0-100	None	In vacuum for 630 hours	Large BPCC, discernible at 130 hours
N16E	60°N	5x6.5 mm	90-10	None	In vacuum for 348 hours	Large BPCC, discernible at 250 hours
N17E	60°R	5x6.5 mm	90-10	None	In air for 64 hours	Very small BPCC
N31E	60°N	4x7.5 mm	90-10	None	In air for 621 hours	Small BPCC, discernible at 380 hours
N33E	90°A	5x6.5 mm	90-10	None	In vacuum for 1034 hours	No BPCC
N35E	90°M	5x6.5 mm	90-10	None	In vacuum for 797 hours	No BPCC
N37E	0°	5x6.5 mm	90-10	None	In vacuum for 805 hours	No BPCC, frosting on scratches
N39E	60°N	5x6.5 mm	90-10	Fired at 1900°C in argon*	In vacuum for 113 hours	Large BPCC, discernible at 50 hours

TABLE 8

ENVELOPE TECHNOLOGY TASK LAMP TEST MATRIX AND RESULTS (Continued)

Lamp Number	Envelope Orien-tation	Envelope Size ID x OD	Alkali Fill K-Rb	Special Envelope Processing	How Tested	Results
N43E	60°N	5x6.5 mm	90-10	Hydrogen gas polished†	In vacuum for 462 hours	BPCC discernible at 417 hours
N47E	60°N	5x6.5 mm	90-10	Acid cleaned	In vacuum for 836 hours	BPCC found in post-test examination
N49L	90°A	5x6.5 mm	90-10	Acid cleaned	In vacuum for 784 hours	No BPCC, but very hazy
K81E	90°A	5x6.5 mm	90-10	Acid cleaned	In vacuum for 397 hours	No BPCC

*by Corning Glass Works, Corning, New York
†by General Electric Company, Vallecitos Nuclear Center, Pleasanton, California

test lamp envelopes of these orientations after up to 1000 hours of operation suggested that perhaps the cracking problem was solved. The 90°A orientation was selected for use because 90° material in the sizes required for lamp envelopes was more readily available than 0° material. Also less bore frosting developed on 90° envelopes during the tests.

In general, the extent of basal cracking was moderate in comparison with EFM-phase lamps, probably largely because of the reduced oxygen levels resulting from operation in vacuum.

Alternate envelope materials, such as ruby and yttrium aluminum garnet (YAG), were considered as backup approaches to solving the BPCC problem. Heavily doped (in excess of 1% Cr_2O_3) single crystal ruby was obtained on a special order from Union Carbide and fabricated into lamp envelopes. However, by the time these envelopes were received, the cleavage cracking problem was under control. Consequently, no ruby envelope lamps were built. YAG material was also obtained from Union Carbide and fabricated into envelopes. Preliminary seal trials with Kovar metal members and short YAG tubes were not successful, indicating that a considerable effort might be required to develop a satisfactory sealing technique for YAG. Accordingly, no further work with this material was done.

Formal activity on the basal plane cleavage cracking task was terminated after adoption of acid-cleaned 90° envelopes for use in third iteration lamps. As noted in Section III-C, cleavage cracking was not a life-limiting mechanism in these lamps. Indeed only minor cracks developed in relatively few of the lamps.

Life testing of fourth iteration lamps revealed that significant basal cracking was still a problem with 0° sapphire, a moot point since 90° material had been adopted as the design standard.

Subsequently, another parameter, oxygen level within the lamps, was found to apparently have a strong effect on cleavage cracking. Calculations showed that nontrivial amounts of oxygen could permeate into operating lamps through the thin walled Kovar endcaps over a period of time to feed the reaction

$$2K + \frac{1}{2}O_2 + 12Al_2O_3 \rightarrow K_2O \cdot 12Al_2O_3$$

cited earlier as probably responsible for cleavage cracking. To counteract this oxygen permeation mechanism additional uranium getters in the form of washers were placed at each end of the lamp interior to intercept the oxygen before it reached the arc discharge. This modification was made on sixth iteration lamps. An additional barrier to oxygen permeation was provided by the oxidation protective vitreous coating, especially when the coating was of sufficiently high initial quality to remain effective throughout lamp life. An indication of the importance of these measures to minimize oxygen permeation and its effect is provided by lamps built to evaluate pointed, pure tungsten cathodes (See Section IV-C). These lamps, numbers 153-X, 163-X, 164-X, and 165-X, had vitreous coatings of excellent quality and the additional uranium getters. In addition, their envelopes were made from 60° material, believed to be the most vulnerable to cleavage cracking. Significantly only minor cleavage cracks developed in but one of the four lamps during life testing to nominally 6000 hours in an air ambient.

2. Envelope Frosting

On this task extensive characterization of crystallite growth and other optical degradation phenomena on the interiors of envelopes was performed using SEM, EDAX, XRD and other analytical tools. The work was carried out at Stanford University under the guidance of Mr. Chris Zercher. Optical deterioration of the envelope bore (i.e., the development of frosting) had been of concern because of possible attendant reduction in laser pumping efficiency.

A typical SEM photograph of a crystallite infestation on an envelope bore after lamp operation is shown in Figure 13. There was sufficient material in this infestation to permit x-ray diffraction to be conducted. As noted in the previous section, the resulting XRD pattern indicated that the compound was $K_2O \cdot 12Al_2O_3$, a potassium beta alumina isomorph slightly less rich in K_2O than is "regular" beta alumina ($K_2O \cdot 11Al_2O_3$). A subsequent check on the XRD power sample by optical emission spectroscopy confirmed the slight K_2O deficiency in comparison with $K_2O \cdot 11Al_2O_3$.

Lamp life testing experience indicated that such surface crystallites invariably formed during extended lamp operation, even in the absence of cleavage cracking that is believed to be caused by the same potassium aluminate compound formation. The severity of frosting, however, seemed directly related to the initial cleanliness of the lamp, to the degree to which oxygen levels in the lamp were controlled, and apparently to sapphire orientation (as noted in the previous section, 0° material seemed to be more prone to become frosted).

It may be that formation of $K_2O \cdot 12Al_2O_3$ by the reaction

$$6K + 37Al_2O_3 \rightarrow 3(K_2O \cdot 12Al_2O_3) + 2Al$$

is inevitable since the reactants, potassium and sapphire, are necessarily present and in contact during lamp operation. However, it appears that by controlling oxygen level the degree of frosting can be restricted to acceptable levels. Induced fluorescence measurements on the previously mentioned experimental electrode study task showed very little fall off with lamp lifetime despite the gradual development of modest crystallite infestations.

B. Efficiency Study

The relationships between laser pumping efficiency and certain lamp design and fill variables, specifically xenon fill

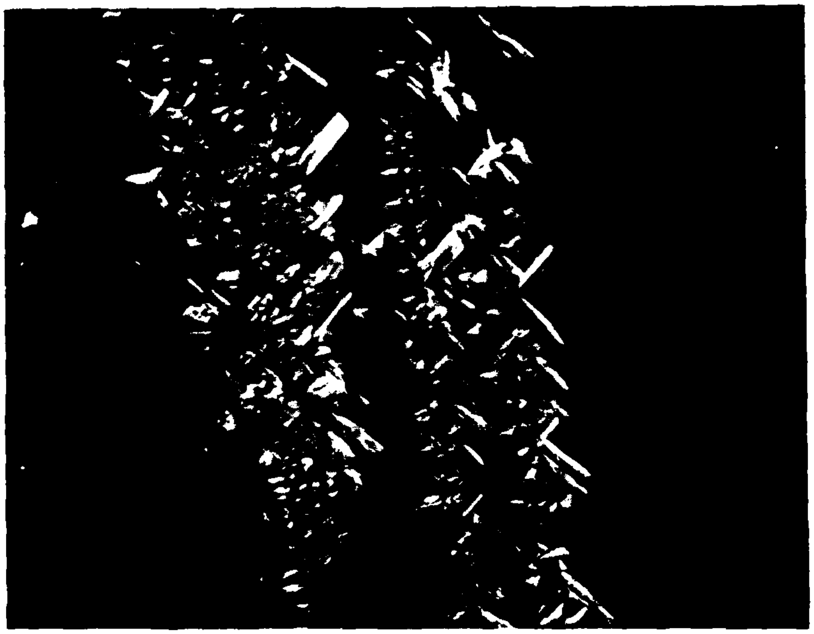


Figure 13. Scanning Electron Micrograph of Potassium Aluminate Crystallites on Envelope Bore

pressure, K-Rb ratio, lamp envelope bore diameter, and arc length, were examined on this task. To evaluate these variables, a number of special lamps were fabricated with different xenon fill pressures, K-Rb ratios, bore diameters, and arc lengths. These lamps were tested in an actual laser pumping situation to provide comparative efficiency data.

Work on prior programs had shown that the efficiency of K-Rb lamps increased significantly with increasing xenon fill pressure, to a lesser but useful extent with increasing proportions of potassium in the K-Rb mixture, and possibly with smaller (4 mm) envelope bore diameters. These findings had led to the establishment of a 100 kPa xenon fill pressure and a 75%K-25%Rb alkali metal mixture as the baseline fill in final EFM-phase lamps (early EFM-phase lamps had a fill of 13 kPa argon and 50%K-50%Rb). The bore diameter had remained at 5 mm because evidence for the superiority of the 4 mm diameter was inconclusive and there was concern that the increased heat loading on the envelope wall of 4 mm bore lamps would hasten frosting reactions or other degradation.

1. Testing Method

All of the efficiency study lamps were tested by MDAC-SL in their laser test bed. In these tests, laser output power per se is not measured. Instead, controlled insertion loss is utilized in the optical cavity and the values of single pass loss (α), saturation parameter (β), and gain (g_0) are determined. Theoretical output power for optimum coupling (P_{opt}) is calculated from these using the relationship:

$$P_{opt} = \frac{\beta}{2} [g_0{}^{\frac{1}{2}} - \alpha^{\frac{1}{2}}]^2 .$$

Both g_0 and P_{opt} are measures of pumping efficiency.

A number of laser test series were conducted at various times during the program. Unfortunately, other laser parameters (especially the condition of the reflective end plate surfaces in the pump cavity) varied sufficiently between the several test series that the measured test parameters were strongly affected. This precluded meaningful comparisons between lamps except within each given test series.

2. Effect of Xenon Fill Pressure

Lamps with a 5 mm bore diameter, a 75%K-25%Rb fill, and xenon fill pressures of 13, 39, 66, 100, 120, and 130 kPa were tested to evaluate xenon fill pressure. The last two fill pressures were of particular interest because they offered the potential of additional efficiency gains over those already achieved by adopting a 100 kPa baseline pressure.

The results of these tests, summarized in Table 9 and plotted in Figure 14, indicate that an optimum xenon fill pressure apparently exists in the range of 120-130 kPa. The baseline xenon fill pressure was kept at 100 kPa despite these results because of concern that the higher ignition voltage associated with an increased xenon fill pressure would be marginal with respect to the voltage stand-off capability of the laser pump cavity.

TABLE 9

LASER TEST RESULTS, VARIABLE XENON FILL PRESSURE

Lamp No.	Xenon Pressure (kPa)	α	β	g_0 (%)	P_{opt} (mW)
N10X	13	.66	.043	2.17	203
N8X	39	.87	.032	2.48	256
N1X	66	.72	.037	2.50	288
125-4	100	.89	.030	2.89	386
N95X	120	.88	.028	2.96	441
N98X	130	.97	.029	3.06	396

NOTE: All lamps filled with 75%K-25%Rb.

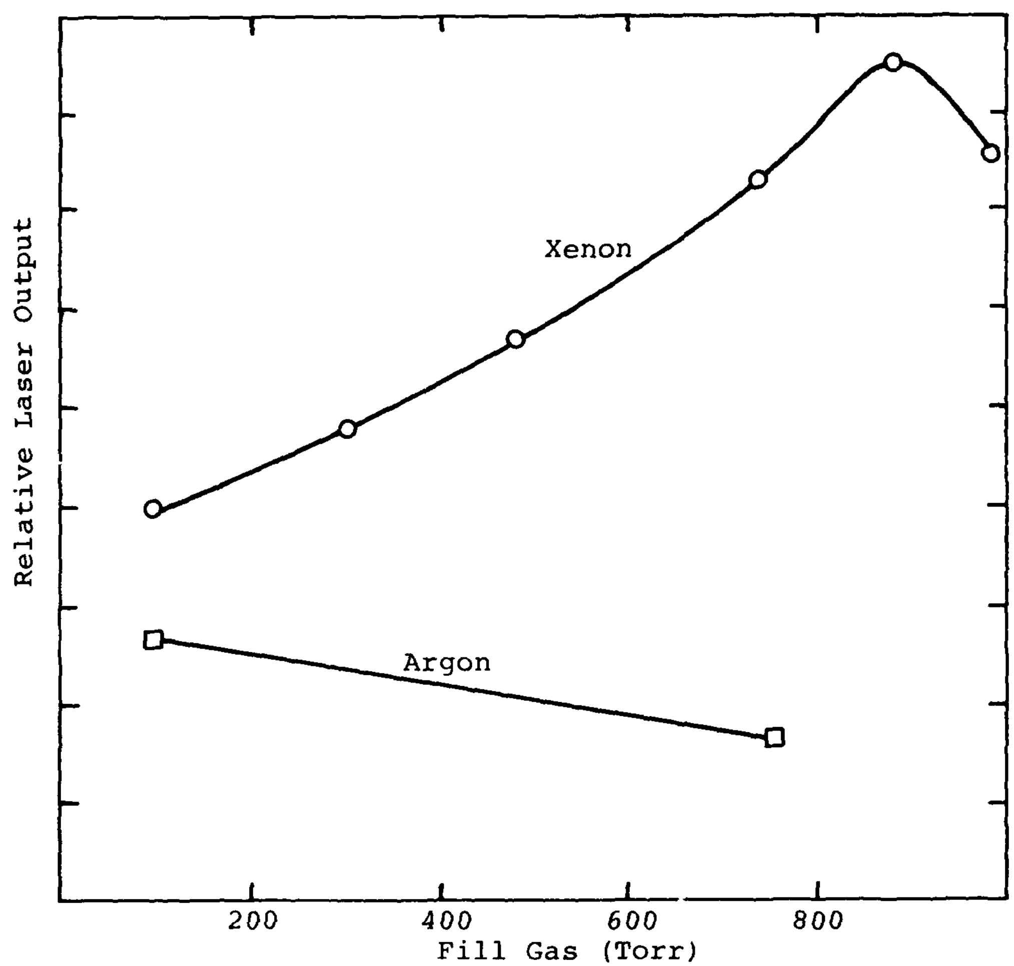


Figure 14. Lamp Efficiency as a Function of Fill Gas Pressure

3. Effect of K-Rb Ratio

Evaluation of the effect of the K-Rb ratio on efficiency was limited to comparisons between 75%K-25%Rb, 90%K-10%Rb, and 100% K fills. These laser tests were conducted in three series spaced months apart. Lamps were substantially identical (all with 100 kPa xenon) except for the K-Rb ratio. The laser pump cavity conditions were different in each of the three tests, however, as reflected in the large difference in absolute values of g_o and P_{opt}.

Test results are shown in Table 10. The first two tests show the 90-10 fill to be slightly more efficient than 75-25. No advantage is indicated for 100% potassium over 75-25 in the third test. However, later tests involving actual output power measurements from an operating laser at GTE-Sylvania indicated a 5-10 percent superiority for the 100% potassium fill over 75-25. (Prototype sixth iteration lamps were used in these tests.)

The 100% potassium fill was subsequently adopted as the baseline fill, in part because of its apparently better efficiency and in part because it is a "safer" fill, i.e., is less likely to be contaminated with oxygen because the additional alkali metal handling required in mixing an alloy (either 75-25 or 90-100) is avoided.

4. Effect of Envelope Bore Diameter

It was postulated that constriction of the wall stabilized K-Rb arc by the use of a smaller bore diameter envelope would provide an efficiency gain over the standard 5 mm bore envelope because of improved optical coupling into the laser rod. If so, the smaller bore envelope could be incorporated into lamps without an undue increase in envelope wall temperature if the outside envelope diameter (6.5 mm) was not changed since heat dissipation is largely controlled by external surface area.

The laser tests on 4 mm and 5 mm bore lamps were performed with two different TEM_{00} mode diameters. As can be seen from the results in Table 11, the 4 mm bore lamp performed as well as or better than the 5 mm bore lamp when the smaller mode diameter was

TABLE 10

LASER TEST RESULTS, VARIABLE K-Rb RATIO

Lamp Number	K-Rb Ratio	α (%)	β	g_0 (%)	P_0 (mW)	Remarks
N23P	75-25	0.48	0.087	1.95	113	Rod temperature 15°C
		0.49	0.074	1.93	128	Rod temperature 14°C
N11X	75-25	0.53	0.078	2.03	124	Rod temperature 14°C
N28X	90-10	0.53	0.079	2.12	134	Rod temperature 15°C
N28X	90-10	1.05	0.029	3.60	529	Lamp at 68 V
		1.03	0.028	3.61	563	Lamp at 69 V
K66S	75-25	1.23	0.027	3.59	460	
K75S	75-25	1.39	0.031	3.84	394	
K77S	75-25	1.16	0.028	3.62	483	
125-4	75-25	0.66	0.033	2.50	354	At 69.8 V, 1st test
		0.60	0.037	2.54	359	2nd test, after lamps below were tested
134-5	75-25	0.71	0.035	2.70	369	
137-5	75-25	0.67	0.035	2.53	342	
140-5	75-25	0.67	0.035	2.59	354	
147-5	100-0	0.70	0.034	2.61	352	At 72.7 V
149-5	100-0	0.74	0.033	2.66	356	At 70.9 V

used but was inferior with the large mode diameter. Again the absolute values of g_0 and P_{opt} were low in the first group due to the absence of reflective end plates in the pump cavity. In general, the results showed that no advantage is gained with the smaller bore lamp. Consequently, the 5 mm bore diameter was retained as the design baseline.

TABLE 11

LASER TEST RESULTS, VARIABLE ENVELOPE BORE DIAMETER

Lamp Number	Bore Diameter	α (%)	β	g_0 (%)	P_{opt} (mW)	Remarks
N23P	5 mm	0.41	0.069	1.71	131	Rod temperature 15°C mode diameter .98 mm
		0.49	0.074	1.93	128	Rod temperature 15°C mode diameter .98 mm
		0.48	0.087	1.95	113	Rod temperature 15°C mode diameter .98 mm
N26X	4 mm	0.49	0.089	2.05	118	Rod temperature 16°C mode diameter .98 mm
N23P	5 mm	1.14	0.025	3.55	537	Mode diameter 1.24 mm
N26X	4 mm	0.96	0.030	3.36	491	Mode diameter 1.24 mm

5. <u>Effect of Arc Length</u>

Two lamps with 47.5 mm arc gaps (compared with the baseline arc length of 63.5 mm) were built, one each with 4 mm and 5 mm bore diameters. The envelopes were of standard length with longer cathode and anode shanks used to produce the shorter arc gap. These lamps were tested in a laser test series along with lamps with standard arc gaps. The laser rod was the normal 66 mm length. As before, reflective end plates were absent from the pump cavity resulting in low absolute values for g_0 and P_{opt}. Also the values of α and β were apparently estimated or only measured once and were assumed to be constant throughout the test. The results (Table 12) indicated no significant difference in efficiency between baseline lamps and lamps with shorter arc gaps.

TABLE 12

LASER TEST RESULTS, VARIABLE ARC LENGTH

Lamp Number	Arc Length	Bore Diameter	α (%)	β	g_0 (%)	P_{opt} (mW)
500	63.5 mm	5 mm	1.0	0.05	1.95	242
N23P	63.5 mm	5 mm	1.0	0.05	1.93	237
			1.0	0.05	1.95	242
N30X	47.5 mm	5 mm	1.0	0.05	1.95	242
N26X	63.5 mm	4 mm	1.0	0.05	2.05	269
N27X	47.5 mm	4 mm	1.0	0.05	2.12	287

C. Electrode Technology

In earlier programs little work had been carried out at ILC on the electrode design or the electrode materials used in K-Rb lamps. Thoriated tungsten had been used for cathodes and either thoriated or pure tungsten for anodes. Both electrode tips had a hemispherical 1.59 mm (0.0625 in) radius. These designs had performed satisfactorily although they were not the products of specific design exercises. Nevertheless, it seemed appropriate to reconsider electrode materials and designs, particularly with respect to the cathode, since it was believed lamp efficiency could be improved by modifications.

When, during the course of work on this program, cathode deactivation became a serious problem, attention on the task turned toward developing a cathode with long term stability, lamp efficiency not withstanding.

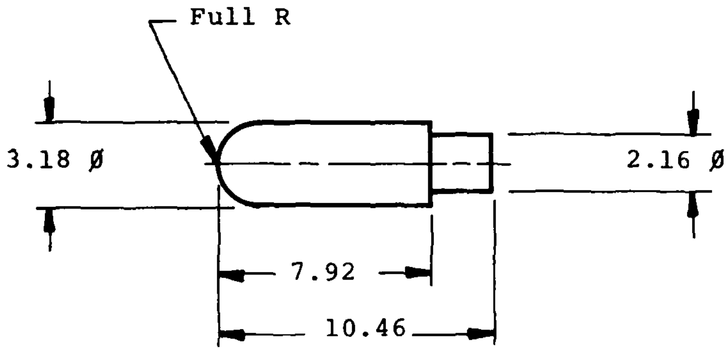
Cathode emission current densities in the subject K-Rb and potassium lamps are relatively modest by arc lamp standards (10-100 A/cm^2) and depend strictly on thermionic emission.

During ordinary operation, the cathode tip surface is activated by the presence of a thin coating of alkali metal. The alkali metal coating is maintained by a dynamic balance of condensing and evaporating alkali metal vapor. Depending on the alkali metal vapor pressure in the lamp and on the cathode surface temperature, the alkali metal coating may be either a bulk coating of at least several atomic layers or a single monolayer. Bulk coverage produces a thermionic work function of approximately 2.2 eV[15]. The monolayer coating has a work function of less than 2 eV because of electron exchange and a resulting dipole moment that exists between chemically absorbed alkali metal atoms and the underlying tungsten. Only moderate cathode temperatures are necessary to produce the required emission current with these low work functions. The cathode fall voltage in the arc discharge naturally adjusts to a level that produces the necessary heating on the cathode by positive ion bombardment. A diffuse arc attachment, i.e., over the full hemispherical tip, is observed in lamps with the original cathode design.

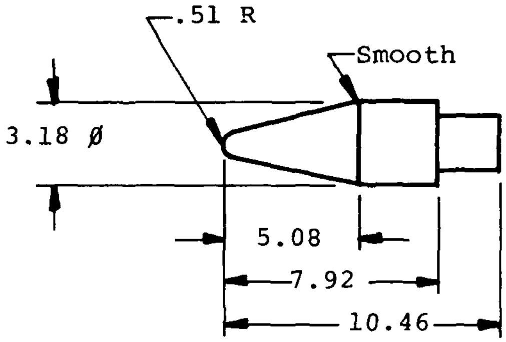
In considering redesign of the cathode, it was reasoned that in the hemispherical cathode design, heating of the cathode surface to necessary emission temperatures was probably inefficient because of the large emitting area and high heat conduction into the bulk of the cathode. Three pointed cathode geometries (Figure 15) were chosen as possible means of improving the efficiency. In these designs, electrons might be emitted from a smaller tip region more efficiently heated by the arc because of reduced heat loss. This might be especially true in the heat choked designs.

As a further modification, pure tungsten rather than 2% thoriated tungsten was used for the cathode material. Since thermionic activation is provided by the alkali metal, the presence of thorium seemed unnecessary (and, as was later determined, a detriment) at least under ordinary operating conditions with the normal vapor pressures of potassium and rubidium.

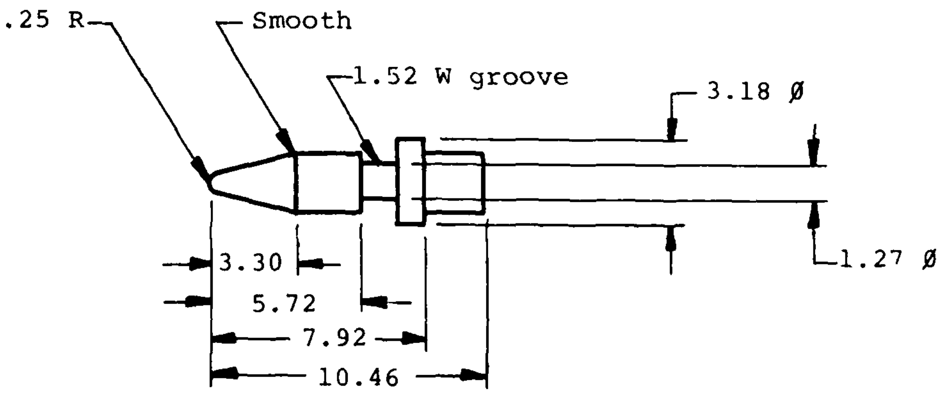
Note: All dimensions are in millimeters



(A) Standard Hemispherical Cathode



(B) Pointed Cathode



(C) Pointed, Heat-Choked Cathode

Figure 15. Experimental Cathode Geometries

Lamps were fabricated with these experimental cathodes and evaluated for radiant efficiency against control lamps with thoriated and pure tungsten cathodes of the standard hemispherical shape. Relative irradiance was measured for each lamp using a silicon photodiode detector. Measurements were taken both unfiltered and with a 0.65-0.85 μm band pass filter. In addition, spectral irradiance curves were obtained for each lamp. The areas under the 700-900 nm segment of these curves were measured to provide a further indication of relative radiant output.

The results of these tests are depicted graphically in Figure 16. The data indicated the apparent superiority of the pointed and heat choked cathodes. Also, the use of thoriated tungsten appeared advantageous.

An additional and interesting result is seen in spectral irradiance curves obtained from lamps with standard and pointed heat choked cathodes (Figure 17). At the same arc voltage, the curve for the pointed cathode lamp is seen to exhibit more self reversal of potassium resonance lines. This implies that a higher potassium pressure is present than in the standard lamps. Equal measured arc voltages are presumably produced because in the experimental lamp the larger positive column voltage drop resulting from higher pressure is compensated by a smaller cathode fall voltage.

Two of the experimental lamps, N34E and N46E, were sent to MDAC-SL for additional evaluation in the laser test bed. Laser gain measurements with these lamps at a single (and not necessarily optimal) voltage failed to show any improvement over lamps with standard cathode designs.

Despite the inconsistency between laser test results and the earlier irradiance measurements, pointed cathodes were used in fourth iteration life test lamps. As noted earlier thoriated tungsten was used for these cathodes instead of pure tungsten because of problems encountered with pure tungsten cathodes in second iteration lamps (discussed in Section III-B) and also because of

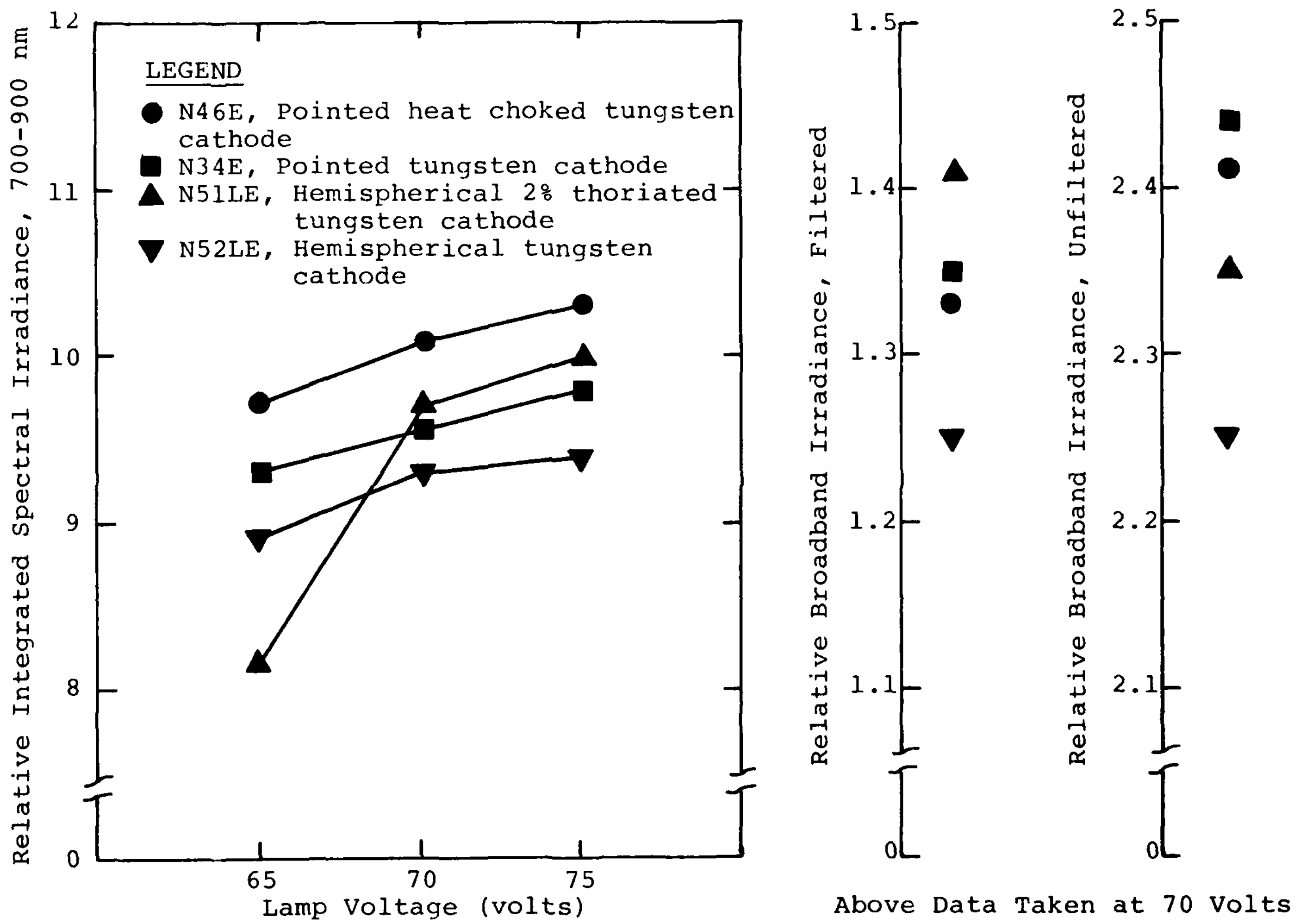


Figure 16. Irradiance Values for Lamps with Experimental Cathodes

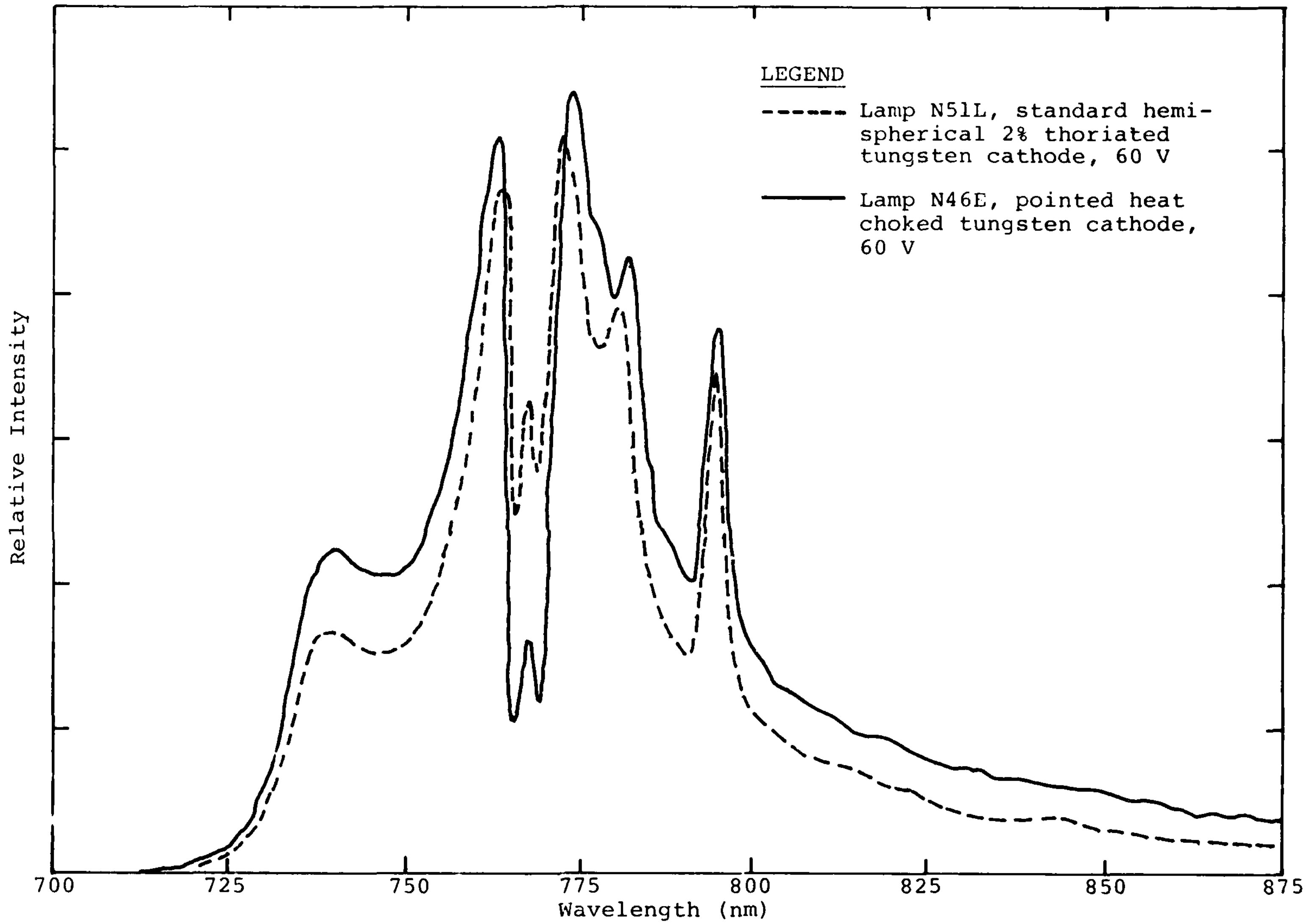


Figure 17. Spectral Irradiance Curves for Selected Lamps with Experimental Cathodes

the apparent superiority of thoriated tungsten in the aforementioned irradiance measurements. As noted earlier, these thoriated tungsten cathodes suffered from deactivation early in life although they seemed to periodically recover and behave normally.

At this point the emphasis on the electrode technology task was shifted towards developing a solution to the cathode deactivation problem. The solution, as it turned out, was simply to switch to the pointed, heat choked pure tungsten cathode previously evaluated for efficiency improvement (Figure 15C).

Assuming that cathode deactivation was indeed caused by "poisoning" of the cathode surface by free thorium, the use of pure tungsten, i.e., the elimination of the source of thorium, seemed to be a logical approach. However, the use of pure tungsten cathodes of the original hemispherical geometry in second iteration lamps had produced some strange and damaging effects during arc ignition. As mentioned in Section III-B, this had been attributed to the excessive power needed to drive the relatively large, bare tungsten tip surface to temperatures necessary to produce adequate electron emission. The more confined and heat choked tip region of the pointed cathode geometry would, it was hoped, be much easier to heat and thus be free of the previously encountered effects. Indeed no problems had been experienced in igniting the two prototype pointed tungsten cathode lamps (N46 and N48) in limited testing. The comparative weakness of the nickel-to-sapphire brazed seals under thermal cycling precluded extensive cycle life testing of these lamps. Lamp N46, in fact, failed by seal fracture after only a few on-off cycles. Lamp N48 was put on minimum cycle life test to determine the long term stability of the pointed tungsten cathode. After 1779 hours of test time cathode behavior was still normal.

As a back-up approach to the pointed tungsten cathode, porous tungsten cathodes impregnated with a barium-calcium-aluminate activating mixture were also evaluated. These cathodes, obtained from the flashlamp production department at ILC, were in the form of short, solid plugs, 3.8 mm in diameter with flat end faces, undoubtedly a non-optimum shape for low current dc lamp use. Two lamps with such cathodes, numbers K115 and K116 were built and life tested along with lamp N48. During the 1600 hours of testing, occasional local incandescence at the arc attachment, generally skewed asymetric arc attachment, and a gradual build-up of cathode material on the adjacent envelope wall were observed. All of these effects could have been the consequence of a nonoptimum tip geometry. In any case, the good performance of the pointed tungsten cathode lamp indicated that that was the best approach to pursue.

Four additional lamps with pointed tungsten cathodes, numbers 153-X, 163-X, 164-X, and 165-X, were built along with fifth iteration lamps and put on life test at ILC to provide a statistically valid indication of the long term, multiple cycle stability of the new cathode design. Except for the cathodes and the use of 60° sapphire for the envelopes, these lamps were identical to baseline fifth iteration lamps. Testing was conducted in ambient air. The lamps were periodically examined for evidence of cathode degradation or basal plane cleavage cracks in the 60° envelopes. Induced fluorescence measurements were also taken on the lamps at approximately 1000 hour intervals.

Results of these life tests are shown in Table 13. All four lamps were still operable after nominally 5500 hours of testing. No cathode problems of any kind were encountered during the testing, thus confirming the effectiveness of the pointed tungsten cathode (in fact this cathode design had been adopted for use in sixth iteration lamps long before the subject life tests were completed).

Of equal importance was the fact that little fall-off in lamp radiant output (i.e., induced fluorescence) had occurred over the 5500 hour test period (Figure 18). The envelopes had remained in good condition (Figure 19) except for haziness near the anodes in lamps that had been inadvertently operated in the xenon mode (see Section V-B). Moderate deposition had occurred adjacent to the electrode tips and

TABLE 13

LIFE TEST RESULTS, EXPERIMENTAL TUNGSTEN CATHODE LAMPS

Lamp Number	Lifetime Cycles	Lifetime Hours	Remarks
153-X	140	5424	Some frosting on envelope caused by xenon mode operation; no BPCC's
163-X	131	6070	Heavy frosting near anode caused by xenon mode operation; at least four small BPCC's
164-X	128	5556	Envelope in good condition; no heavy frosting or BPCC's
165-X	124	5576	Envelope in good condition; one small BPCC

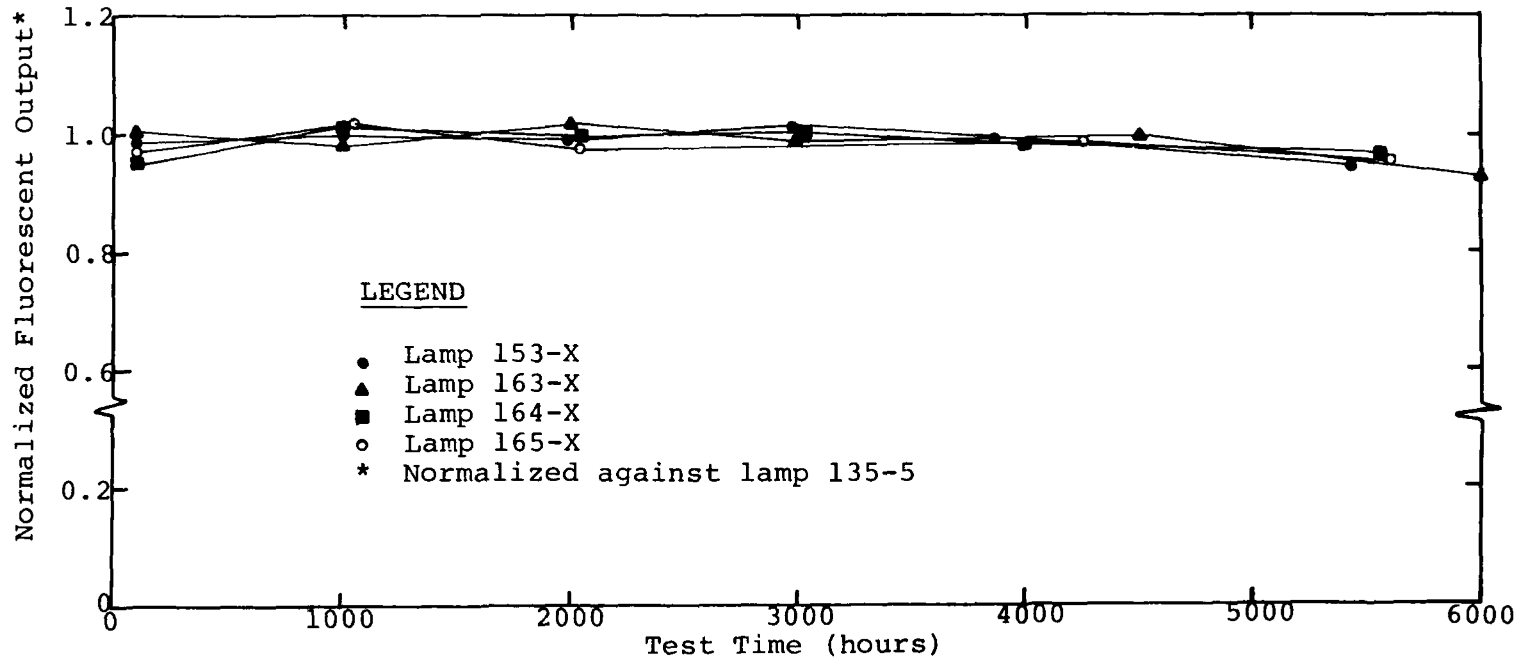


Figure 18. Output vs. Lifetime for Experimental Lamps with Pointed Tungsten Cathodes

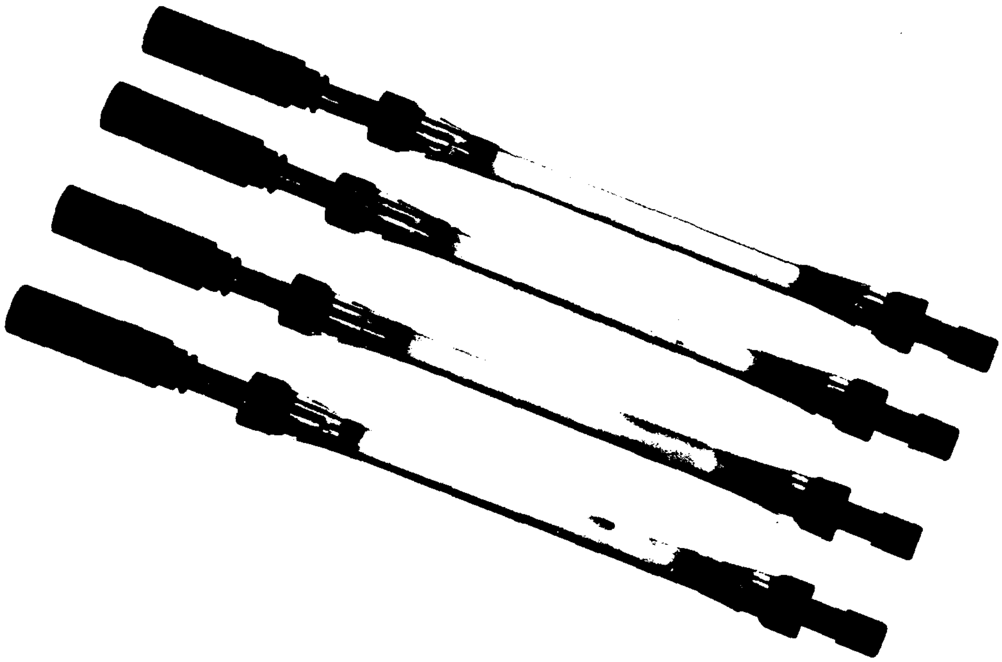


Figure 19. Sapphire Envelopes after 5500 Hour Life Test, Experimental Cathode Lamps

many small aluminate crystallites had grown on the bore surface. Nevertheless, fall-off in induced fluorescence was only 8 percent in the worst case.

Survival of all four lamps to nominally 5500 hours contrasted with results of life tests on baseline fifth iteration lamps where a significant fraction of the lamps had failed prior to the 5000 hour mark. This is probably because of the uniformly high quality vitreous overcoats on the four experimental cathode lamps (all would have been catagorized as "group D" lamps prior to testing as described in Section III-E) and the fact that no cathode deactivation and attendant cathode end overheating occurred.

Finally only minor basal plane cracking was observed in but two of the four lamps, apparently reflecting the importance of low oxygen levels as previously mentioned.

D. Protected End Seal (PES) Lamp Development

During the EFM-phase lamp development program, significant progress was made in the improvement of the PES lamp design. In particular, the feasibility of constructing PES lamps with very refractory and thus potentially long lived end seals was demonstrated. Niobium-to-sapphire seals on the primary lamp envelope were made by chemical vapor deposition (CVD) of niobium directly onto the sapphire. Endbell frit seals were made using a high-melting calcium-aluminate composition. It was concluded that the PES lamp concept was well worth pursuing on the present SFTS program as a backup design to the Kovar and nickel endcap lamps.

On this task, four subtask activities were undertaken:

1. Improvement of the sapphire-to-sapphire endbell frit seal design to prevent cracking during fabrication.
2. Improvement of the niobium CVD process to alleviate the problem of leaks along the niobium/sapphire interface.

3. Modification of anode and cathode endbell designs to eliminate possible self constraint stresses caused by differing thermal expansion of structural components.
4. Fabrication and life testing of lamps as improvements in design and technology permitted.

Problems with frit seal cracking and general lamp fabricability persisted early in the task although significant progress was made on CVD seal development. Unavoidable delays in obtaining usable CVD-sealed envelope assemblies and a pressing need to concentrate program resources on Kovar endcap lamp development finally led to cancellation of PES lamp development. Accomplishments on the four subtasks are reported below.

1. Frit Seal Improvement

It was believed that frit seal cracking might be the consequence of a deficient joint design. Specifically, the localized capillary flow of molten sealing glass into the tight annular space between the primary sapphire envelope and the overlapping sapphire endbell sleeve (see reference 6, Figures 1, 2, and 3) was thought to promote regions of high mechanical stress in the joint. Accordingly, the joint design was modified with a relief groove machined into the sapphire envelope adjacent to the intended butt seal surface to eliminate capillary forces and cause the glass to remain in the intended area.

Short sapphire-to-sapphire seal trial assemblies were fabricated successfully with the modified design. This success prompted incorporation of the design into PES lamps to be built with EFM-phase residual envelope assemblies (see Section 4 below). No further work was carried out on frit seal development.

2. CVD Seal Development

A purchase order was let to Chemetal* and Ultramet*, working as a team, for a CVD process parameter study aimed primarily at improving the vacuum tightness yield of niobium-sapphire seal composites. Ultramet performed the actual coating work and Chemetel provided analytical services including optical and scanning electron microscopy of sample seal cross sections.

Fifteen short CVD-sealed sapphire test pieces were fabricated to evaluate the effects of process variables. The test pieces were geometrically identical to actual lamp envelope ends. Process variables evaluated included sapphire substrate temperature during deposition, deposition rate (controlled by the temperature of the niobium chlorinator), and the inlet ratio of gaseous precursors (Cl_2 and H_2). To facilitate process control, a microspot pyrometer for substrate temperature measurements and mass flow meters for monitoring of gas mixture ratios were employed. The samples produced were evaluated by careful visual inspection, helium leak checks, ductility (crush) tests, and thermal cycling tests.

The results of the parameter study indicated that substrate temperature and, to a lesser extent, deposition rate had noticeable effects on the quality of the niobium coating. The chlorine-hydrogen mixture ratio appeared to be relatively unimportant. Significantly, the final substrate temperature selected was considerably higher than had been used in previous EFM-phase CVD seals.

One of the optimized CVD seal trial assemblies was supplied to ILC for thermal cycle testing. This sample was enclosed in an evacuated, uranium-gettered, fused quartz capsule and was cycled several hundred times between room temperature and 750°C. It remained vacuum tight after this testing.

Following the successful development work on CVD seals, five CVD-sealed envelope assemblies were procured and placed in inventory at ILC.

*Both companies are located in Pacoima, California.

3. Endbell Design Modification

The PES lamp endbell designs were modified to eliminate possible thermal self constraint stresses. This was accomplished by using flexible internal electrical leads and relying on the external sapphire and metal endbell sleeves as structural support members.

Parts sets reflecting the new design were fabricated for use on the first trial lamps to be built on the program. No further work was done on endbell designs.

4. Lamp Fabrication

Early in the program, two attempts were made to fabricate PES lamps that embodied the modified endbell and frit seal designs (Figure 20). Two CVD-sealed envelope assemblies procured on the previous EFM phase program were used for these lamps. The envelope assemblies were first returned to Insaco for grinding of the new relief groove adjacent to the frit seal joints.

During fabrication, the first envelope assembly developed a CVD seal leak during the endcap-to-envelope welding operation. These weldments were successfully made on the second assembly but in the subsequent frit sealing operation the sapphire envelope and endbell sleeve cracked at one of the frit seals during cool down. No further work was done on PES lamp fabrication.

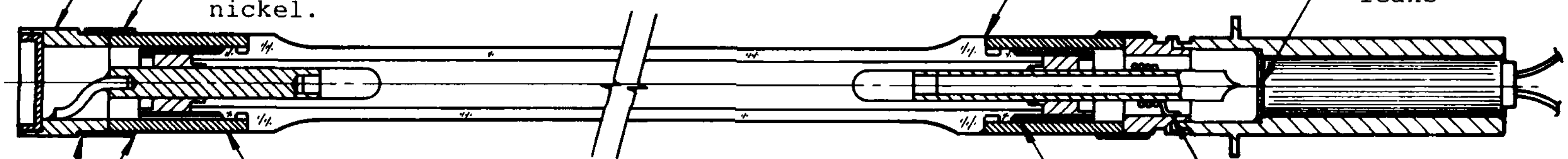


Figure 20. Protected End Seal (PES) Lamp Design

E. Kovar Oxidation Protection

Protection of Kovar from oxidation was of critical importance because almost all lamp failures were caused by oxidation, either in the brazed envelope seal region or in the endcap weldments. The two oxidation-induced failure mechanisms were basically different. Oxidation in the brazed seals seemed to occur along Kovar grain boundaries previously penetrated by liquid phase during the brazing operation thus did not represent oxidation of Kovar per se but of a Zr-Fe-Ni phase instead (see Figure 4). Weldment oxidation, on the other hand, seemed to reflect the intrinsic oxidation behavior of Kovar. Oxidation again occurred along grain boundaries, proceeding across the relatively thin wall until the intergranular oxide stringer reached the inside surface at which point alkali metal attacked the oxide phase and created leaks (Figure 7).

A nickel electroplate of 0.025-0.050 mm thickness, applied to the Kovar endcaps after completion of lamp assembly, was used for oxidation protection on third iteration lamps. This approach effectively prevented weldment leak failure but not oxidation at the brazed seals. As described earlier, most third iteration lamps failed by oxidation leaks in the seal area. The poor protectiveness of the nickel plating was obviously due to lack of adherence to the zirconium-containing endcap surface adjacent to the brazements.

A vitreous overcoat (Owens-Illinois Article 1338 substrate glaze) was used on fourth iteration lamps. The coating was applied to the endcaps and seal areas as a powder suspended in a nitrocellulous laquer and air fired to fuse the glass and bond it to the Kovar substrate. No failures due to oxidation at the brazed seals occurred in fourth iteration lamps attesting to the effectiveness of the vitreous coating there. However, oxidation-induced leakage in the weldments was a predominant failure mode and seemed to be associated with excessive substrate oxidation that occurred during the glazing operation itself and perhaps with faults in the coating.

On the basis of experience with third and fourth iteration lamps the vitreous overcoat was concluded to be the most promising approach for oxidation protection. The present task was undertaken to evaluate various glaze coating compositions and to improve coating application techniques.

Three glaze compositions were initially evaluated:

1) Owens-Illinois Article 1338 Substrate Glaze - a borosilicate glass with a 750°C nominal firing temperature.
2) Owens-Illinois Article 1545 Substrate Glaze - a $PbO-ZnO_2-B_2O_3$ glass designed to fuse and recrystallize (for improved strength) at 650°C.
3) Corning Code 7052 glass - a borosilicate glass commonly used in seals to Kovar with a fusing temperature above 900°C.

All of the glasses have thermal expansion coefficients close to that of Kovar and Al_2O_3.

In the first experiments each glass was evaluated for ease of application using various types of glass powder slurries and application techniques. Glass coatings were applied to the Kovar endcaps of standard brazed seal trial assemblies (see Section IV-F). The best slurry was found to be a mixture of glass powder and a commercial nitrocellulose-base laquer (Corning Suspension Vehicle). The 7052 and 1545 glasses were easy to apply by all of the techniques tried including dipping, spraying (with an air brush), and brushing. In contrast, a continuous, uniform coating was difficult to produce by any of the above techniques with the 1338 glass.

The 1338 glass fused into a glassy coating at 750°C in air. The 1545 glass also required a 750°C firing temperature to produce a fused coating despite the supplier's recommendation of a 650°C firing temperature. Firing at 1000°C was required to fuse the 7052 glass.

Completeness of glass coverage on the fired samples varied. The 1338 and 7052 glasses did not wet the inside corner formed by the juncture of the sapphire envelope and the Kovar cup, instead forming a meniscus just outside of the corner. Other small bare spots on the Kovar also were typical in 7052 coatings, the unprotected Kovar being heavily oxidized as a result of the 1000°C glass firing temperature.

The coated samples were held at 550°C for 190 hours in an air oven and thermal cycled 500 times between room temperature and 650°C. Post-test inspection showed that the 1338 glass had developed circumferential cracks in the aforementioned sapphire-Kovar juncture region (similar cracking was experienced in fourth iteration lamps but apparently did not compromise the oxidation protection of the brazement). The other glasses were unchanged in appearance.

Based on these preliminary results the 1545 glass was chosen for further evaluation. The 7052 glass required an impractically high firing temperature and the 1338 glass was more difficult to apply than the 1545 coating.

Experiments were conducted to determine a proper firing schedule for the 1545 glass to produce the desired recrystallized condition. Until now a 750°C firing had been used but produced a vitreous, not recrystallized coating.

The 1545 glass powder slurry was applied to clean sapphire discs, dried, and immersed in an air oven for five minutes each, reaching final temperatures in the range of 575° to 800°C (depending on the oven temperature). No fusion occurred below 600°C. Samples heated to temperatures between 600° and 700°C apparently fused, forming an opaque glass. At temperatures above 700°C, a very bubbly, porous glass was formed indicating that a volatile constituent was evolving. A transparent, clear, completely fused condition was obtained at temperatures above 775°C.

The recommended recrystallization heat treatment (one hour at 640°C) was then performed on three samples, one prefused at

800°C, another prefused at 675°C, and a third fresh specimen not previously fired. The first sample showed some evidence of surface devitrification but remained substantially transparent and glassy. The second and third samples became powdery and could easily be scraped off the sapphire substrate. The strong, dense recrystallized condition was not being produced.

Owens-Illinois was contacted for consultation on firing of the 1545 glass. Independent experiments in their laboratory confirmed the above finding, i.e., the advertised final properties of the glass could not be produced. The supplier could offer no explanation for the problem nor suggestions for its resolution. Consequently, work on the 1545 glass was discontinued and efforts to develop effective application methods with the 1338 glass renewed.

In order to maximize the bonding strength between the glass and Kovar substrate, a Kovar preoxidation procedure was first developed (preoxidation is common practice in glass-to-metal seals). Kovar discs were air fired at various temperatures for various times and evaluated for oxide adherence and weight gain per unit area. The 1338 glass was then fired onto the preoxidized samples at 800°C for ten minutes and the resulting glass coatings evaluated for adherence to the substrate by bending the discs. Based on the results of this work a 750°C/20 minute preoxidation schedule was adopted.

A second group of Kovar discs were preoxidized using the newly adopted firing schedule and then coated with 1338 glass fired on at 750°C or 800°C for various times from 5 to 20 minutes to determine the best glass firing schedule. Best results (fewer bubbles and other coating faults) were achieved at 800°C for ten minutes. This schedule was adopted.

By this time construction of fifth iteration lamps for life testing was well along. Several lamps had already been completed with 1338 protective coatings fired on at 750°C. The balance of lamps were coated using the new 800°C firing schedule, resulting in a significant improvement on coating quality (reflected in the much longer lifetimes of these lamps in comparison with the group average).

Improvements were also made in the technique for applying the glass slurry to the lamp. After a good deal of trial and error (much of it on the above mentioned fifth iteration lamps) a manual application method using a small spatula to apply a thick pasty slurry to the Kovar including the critical weldment and brazement regions was found to be most effective.

An indication of the progress made during this period is the long lifetimes (5500 hours and still operable) and zero-failure rate of the experimental pointed tungsten cathode lamps built immediately after completion of fifth iteration lamps.

Some time later, when life testing of fifth iteration lamps was well along, a renewed interest developed in improving Kovar oxidation protection, largely because several fifth iteration lamps and one laser test lamp had failed due to oxidation-induced weldment leaks.

A formal experiment was undertaken to provide better information on the oxidation behavior of Kovar under controlled conditions. Simple welded specimens (Figure 21) closely simulating the end structures of lamps were fabricated. Seven such specimens were coated on half (180°) of the circumference including the entire weldment lip with the 1338 glass using standard procedures. The other half of each sample was left bare. Other samples were not glazed at all. An additional three samples were fabricated with Pd-Co (Palco) brazing alloy intentionally filleted up the inside wall of the weldment lips prior to welding (microsections of several failed lamps showed that the fillets on the electrode stem brazements extended into the weldment areas and possibly influenced oxidation behavior there). The samples were then subjected to 120 hour exposure in air at various temperatures as shown in the test matrix (Table 14) followed by metallographic examination.

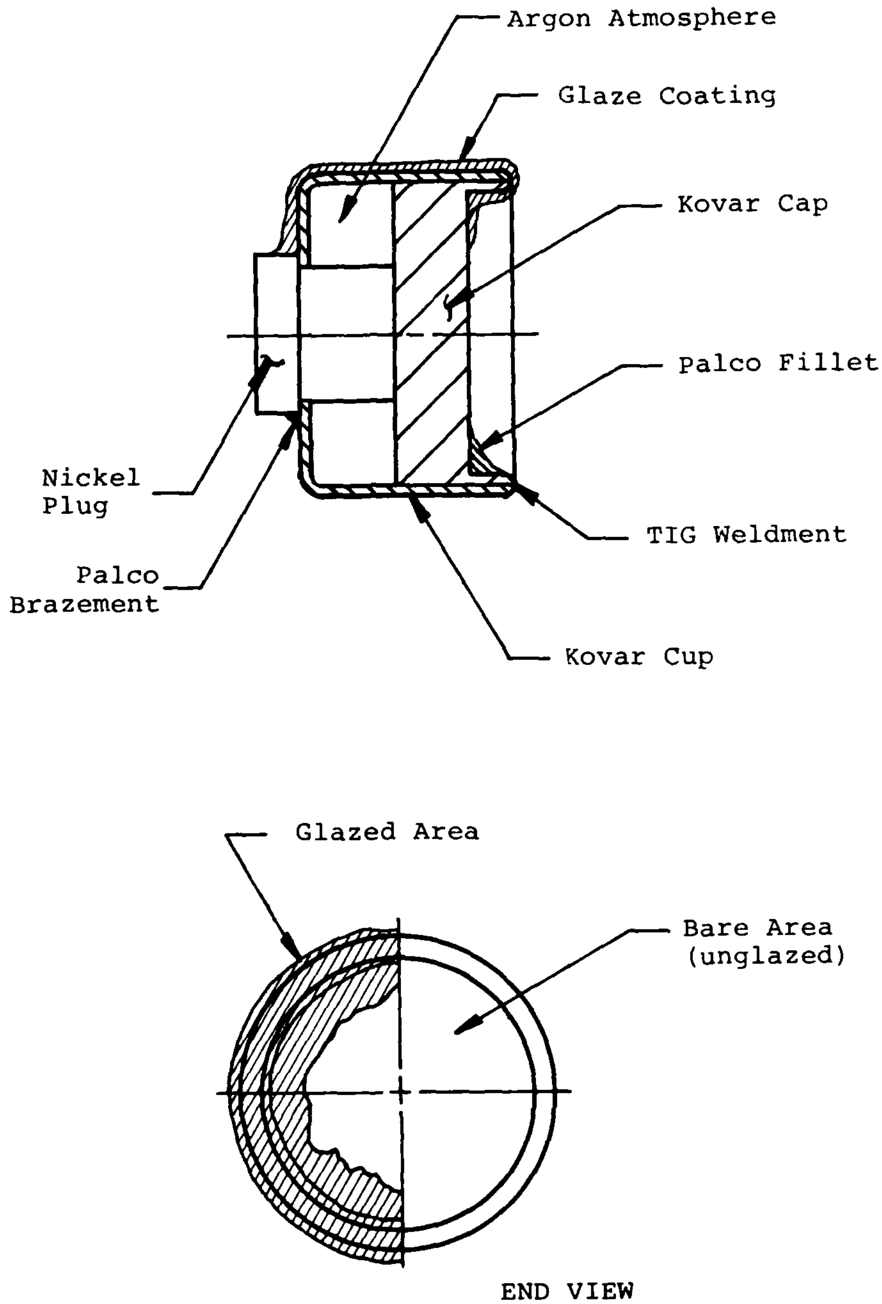


Figure 21. Kovar Oxidation Study Test Specimen

The experiment was designed to provide the following information:

1) oxidation behavior as a function of exposure temperature
2) comparative oxidation in protected and unprotected areas
3) comparative oxidation in welded and unwelded regions
4) the effect of the 800°C glazing cycle on oxidation
5) the effect of the presence of Pd-Co brazing alloy on oxidation

TABLE 14

EXPERIMENTAL MATRIX, KOVAR OXIDATION EXPERIMENT

Sample No.	Glaze Coating	Test Temperature
1	no	Not exposed (control sample)
2	yes	Not exposed (control sample)
3,4	yes	600°C
5,6	yes	700°C
7,8	yes	800°C
9	no	600°C
10	no	700°C
11	no	800°C

Note: Samples 4, 6, and 8 had Pd-Co brazement fillets extending into the weldments.

Results, based primarily on post-test metallographic examination, were as follows:

1. Minimal surface and intergranular oxidation occurs as a result of the 800°C glaze firing cycle (Figure 22).

2. After 120 hour exposures at 600 and 700°C, intergranular oxidation to finite depths (less than 0.1 mm) occurs in both glaze-coated and bare regions of the Kovar (Figure 23). However, virtually no surface oxidation occurs in glazed areas contrasted with a definite surface oxide layer in unprotected regions.
3. Intergranular oxidation seems to occur more rapidly in the weldment areas than along the side walls of the Kovar (Figure 24), perhaps due to the character of the weldment metallurgy.
4. Samples with Palco intentionally filleted into the weldment areas appeared no different for ordinary samples. The effect of the Palco, however, may be to impose thermal expansion mismatch stresses on the Kovar during thermal cycling (not done in this experiment) thus accelerating oxidation processes.
5. No apparent difference was seen between unglazed samples and bare regions of glazed samples.
6. After 120 hours at 800°C the glaze coating had completely deteriorated (no glassy layer remained). Probably the glaze devitrified and intermixed with oxides formed on the Kovar. Nevertheless, the degree of surface oxidation was considerably less in the glazed regions in comparison with bare areas (Figure 25) except in weldment areas where oxidation was severe in all cases.

The apparent inability of the glaze coating to prevent some degree of intergranular oxidation even at the lower 600°C temperature typical of endcap temperatures in operating lamps led to the decision to explore alternate oxidation protection methods. In particular, the use of nickel electroplating, at least to protect the weldment regions, seemed to have merit, especially since no weldment leaks occurred in nickel plated third iteration lamps

Figure 22. Oxidation Produced During Glazing

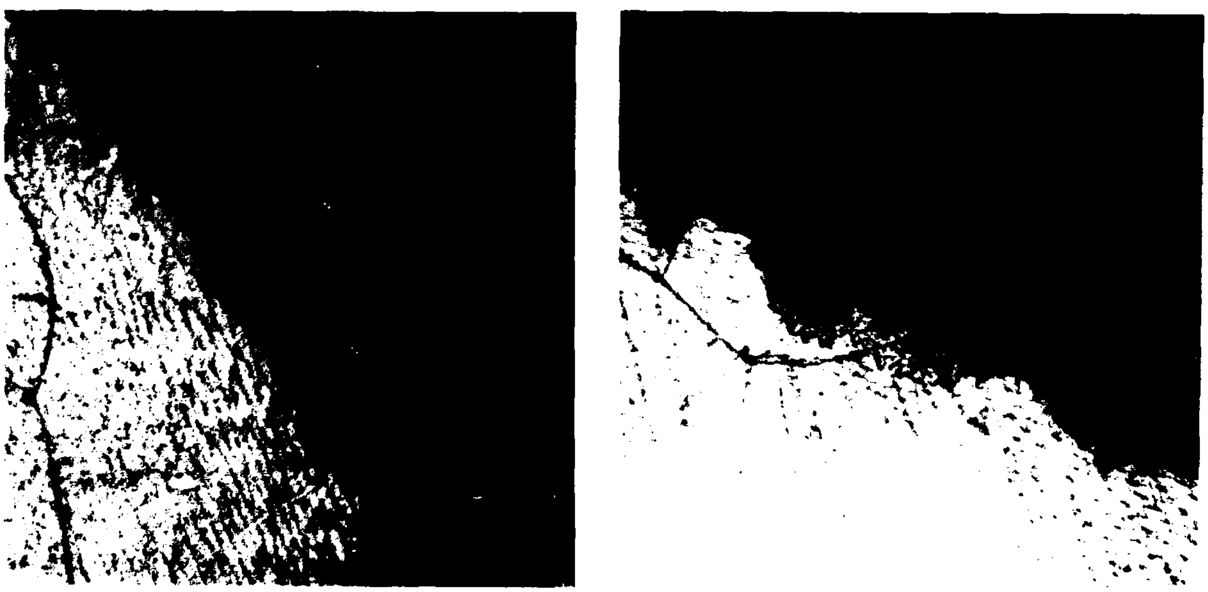


Figure 23. Comparative Oxidation in Protected and Bare Regions

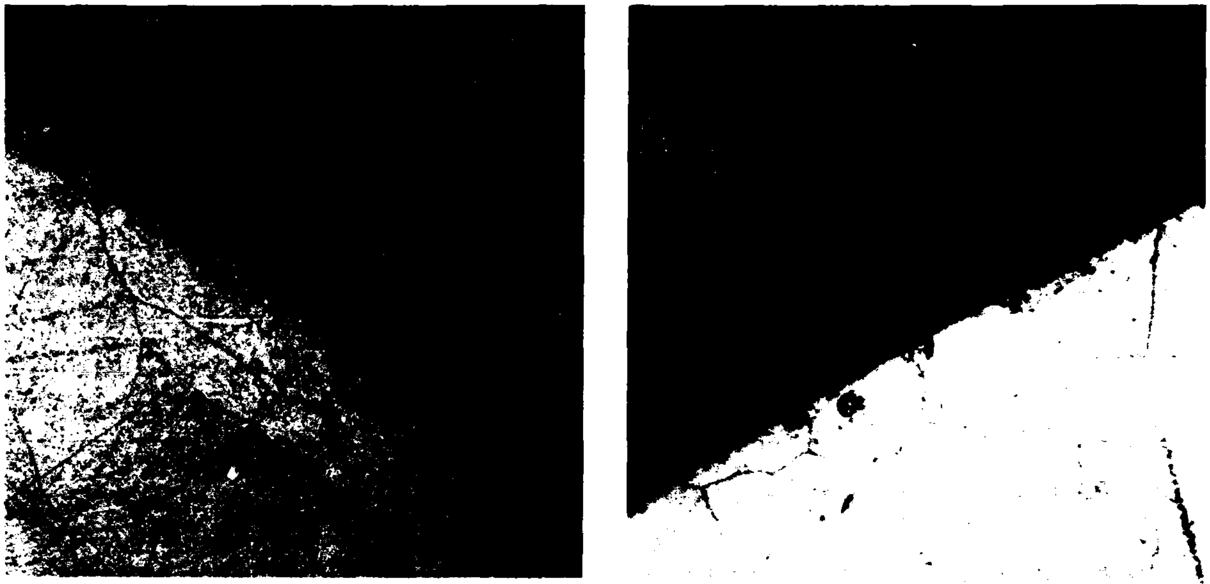


Figure 24. Comparative Oxidation in Weldments and Sidewalls

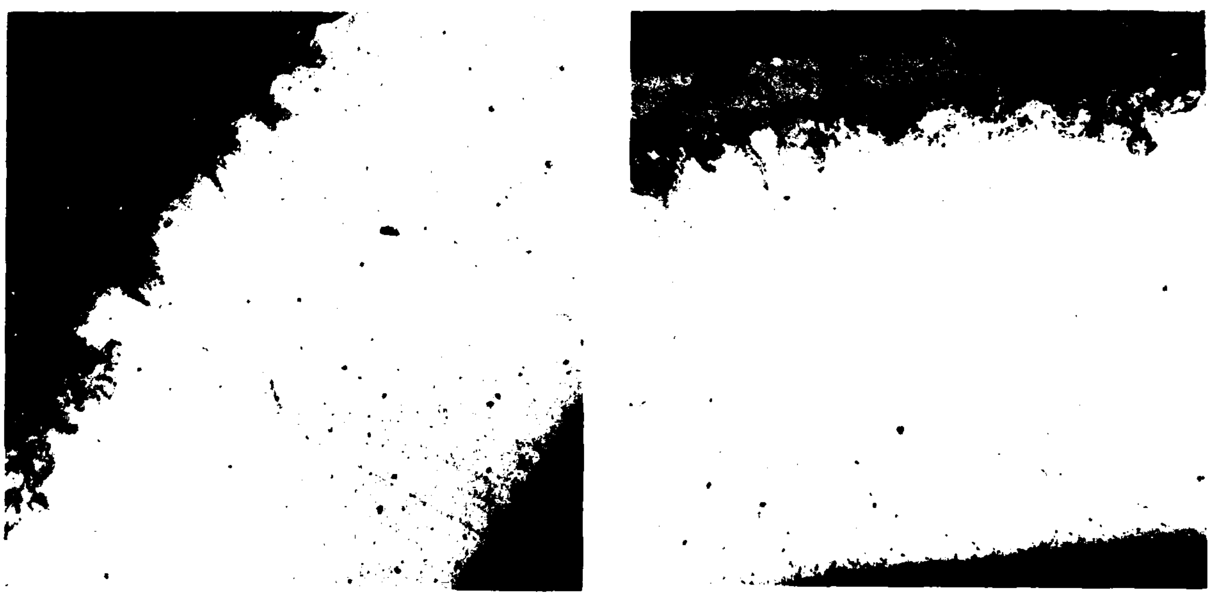


Figure 25. Comparative Oxidation in Protected and Bare Regions After 800°C Exposure

during life testing. A "hybrid" protective coating was conceived, combining nickel plate protection of the weldments with 1338 glaze protection of the brazed seal areas.

Kovar cups were used at test vehicles for evaluation of the hybrid coating. The brazed seal area of the cups was masked with a organic laquer and the unmasked surfaces nickel plated to various thicknesses ranging from .013 to .050 mm. The laquer was then dissolved in acetone and the unplated areas coated with the 1338 glaze by the standard procedure. The glaze coating was applied so that it overlapped by 1 mm or so onto the plated region.

In the first samples so prepared considerable bubbling occurred in the overlap area, the severity of which seemed in proportion to the underlying plate thickness.

A second group of samples was made after refurbishing the plating bath. Little or no bubbling occurred in these samples, plated to thicknesses of 0.25 to 0.37 mm. The samples were thermal cycled 100 times in air to 650°C and held for 100 hours at that temperature. Except for a light tarnish on the nickel plating, their appearance was unchanged after this test (Figure 26).

The press of time did not permit further experimental evaluation of the hybrid protection coating. Based on the successful results described above the approach was adopted for use on sixth iteration lamps.

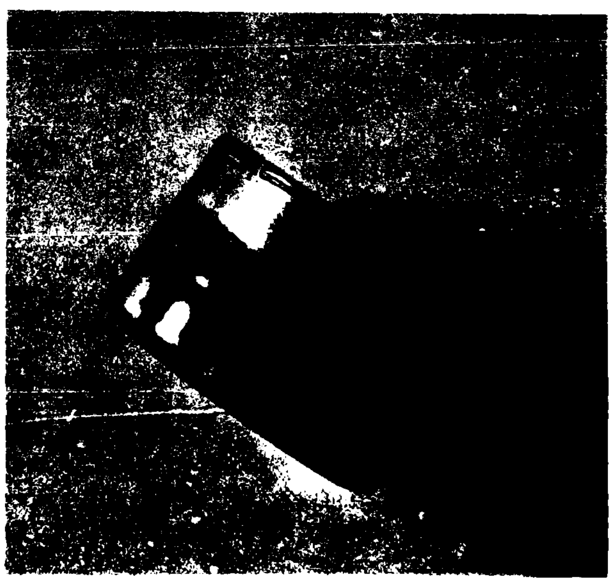


Figure 26. Endcap with Hybrid Protection Coating

F. Brazed Seal Development

The major part of the work on this task was conducted early in the program, prior to selection of the third iteration lamp design, and was supported under the MDAC-SL subcontract. This early activity is briefly summarized in Section 1 below. Later a novel technique was conceived and briefly evaluated for fixturing lamp envelope assemblies during brazing. The technique employed differential thermal expansion to generate an axial load on the stacked parts being brazed (replacing the conventional use of large weights) to overcome the inadequate flatness of the Kovar seal cups. This work is described in Section 2.

1. Preliminary Work (MDAC-SL Funded)

The purpose of the preliminary work on brazed seals was to experimentally evaluate various modifications to zirconium-brazed lamp end seals. It was recognized that the development of leaks in the seals of EFM-phase lamps was related to an initial intergranular penetration of the nickel or Kovar base metals by the brazing liquid and the subsequent selective oxidation of the penetrant phase during lamp operation. Because of the thinness of cup walls, 0.25 mm, the oxidation-prone penetrant phase frequently extended completely through the cup wall. It was along these paths that leakage would eventually occur.

Three seal modifications were evaluated:

1. Use of the endcaps of high purity grade 270 nickel instead of commercial grade 200 nickel in nickel endcap lamps.
2. Reduction in the amount (i.e., thinner braze washers) of zirconium used in both nickel and Kovar endcap lamp seals.
3. Increase in the wall thickness of the nickel and Kovar cups.

It was reasoned that 270 nickel might be more resistant to intergranular erosion than 200 nickel because of its higher purity (less segregation of impurities at grain boundaries). Also, it was judged that a reduction in the amount of zirconium used in the brazement would reduce base metal penetration. The use of cups with thicker walls would, it was believed, at least increase the leak path length and possibly would permit the retention of a zone midway through the cup wall that was unpenetrated by the brazing liquid.

Sample seals were fabricated using short sapphire tubes and the same seal cups and brazing washers as used in lamps. The brazed seal assemblies were visually inspected to assess the degree of wetting of the sapphire by the brazing alloy at the joint interface and were then helium leak checked. Most of the leak-tight seal assemblies were subsequently fabricated into sapphire/metal capsules (Figure 27). These capsules were processed, charged with alkali metal, and closed off in the same fashion as were lamps. To simulate lamp operation, the capsules were then subjected to thermal cycling in air between room temperature and 650°C with frequent prolonged soaks at the higher temperature.

The results of the experimental work showed that of the three seal modifications considered, only the increase in cup wall thickness was effective. Seals made with 270 nickel cups seemed more subject to seal stress fracture than those made with 200 nickel cups. The reduction in thickness of the zirconium brazing washer caused poorer interface wetting because of the decreased amount of brazing liquid. However, a reduction to 0.017 mm zirconium braze washer thickness in the Kovar seals was adopted despite wetting problems in order to minimize the localized flow of brazing liquid upon the cup walls.

Thermal cycle and soak test results on nickel and Kovar endcap capsules with 0.25 mm and 0.38 mm wall thickness are shown in Table 15. The thicker wall Kovar design was clearly superior. These results were in large part responsible for selection of the

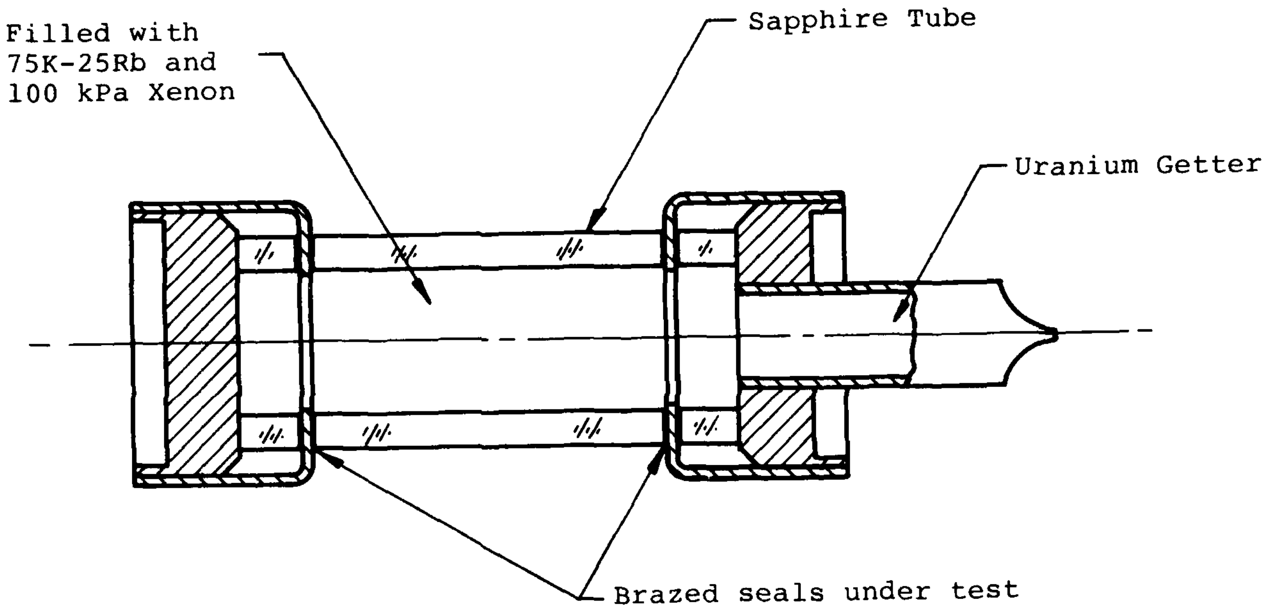


Figure 27. Brazed Seal Test Specimen Design

TABLE 15

TEST RESULTS ON BRAZED SEAL SAMPLES

Sample No.	Cup Material	Cup Wall Thickness (mm)	Brazed with (mm)	Lifetime Cycles	Lifetime Hours	Remarks
124	200 Nickel	.38	.0088 Zr	2525	1733	Sapphire crack near seal
125	200 Nickel	.38	.0088 Zr	-	-	Lost in fabrication, bad weld
126	200 Nickel	.38	.0063 Zr	2434	1008	Sapphire crack near seal
127	200 Nickel	.38	.0063 Zr	2741	1893	Leak in seal fillet
128	Kovar	.38	.0088 Zr + .038 Ni	334	317	Leak in seal fillet
129	Kovar	.38	.0088 Zr + .038 Ni	334	224	Leak in seal fillet
130	Kovar	.38	.013 Zr + .063 Ni	120	72	Leak in seal fillet
131	Kovar	.38	.013 Zr + .063 Ni	269	112	Leak in seal fillet
132	200 Nickel	.25	.0088 Zr	2113	1275	Sapphire crack near seal
133	200 Nickel	.25	.0088 Zr	149	40	Leak in seal fillet
134	200 Nickel	.25	.0063 Zr	-	-	Not tested
135	200 Nickel	.25	.0063 Zr	2113	941	Leak in seal fillet
136	Kovar	.38	.017 Zr	3617	2381	Leak in seal fillet
137	Kovar	.38	.017 Zr	3554	2381	Leak in seal fillet
138	Kovar	.38	.021 Zr	2662	1733	Leak in seal fillet
139	Kovar	.38	.021 Zr	2560	1890	Leak in seal fillet

thick walled Kovar endcap design in third and fourth iteration lamps.

During the course of work on Kovar seals, it was discovered that the Kovar cups being used were not sufficiently flat on the seal surface. Although the cups were generally flat to within 0.025 mm, extensive unwetted or marginally wetted areas remained in the brazed seals. Attempts to obtain flatter cups from the vendor were not successful. Finally it was found that marginally acceptable flatness could be obtained by manually sanding the seal surface on 600 grit carborundum paper.

Manual sanding of the Kovar cups prior to brazing remains a standard step in lamp fabrication. After sanding, careful screening of the cups for flatness using a straight-edge under a microscope is necessary. Also it is important to avoid removing excessive metal stock during the sanding operation. The resulting thin wall can cause short oxidation lifetime (as in one of the third iteration life test lamps).

2. Differential Thermal Expansion Brazing

In the standard brazing procedure a tungsten weight of approximately 1 kg is stacked on top of the envelope assembly to hold the parts in contact until the brazing temperature is reached. The weight is not nearly sufficient to press down unflat areas in the Kovar cups, however, and a weight sufficient to do this would be impractically large.

Another means of "weighting" a brazing assembly is to utilize differential thermal expansion to advantage. For example, by sandwiching the brazing assembly between two end plates and connecting the end plates with a tie rod having a lower thermal expansion coefficient than the brazing assembly, a significant axial compressive load can be generated on the brazing assembly when the overall assembly is heated.

In the differential thermal expansion brazing fixture evaluated on this task (Figure 28) a molybdenum rod is used to connect

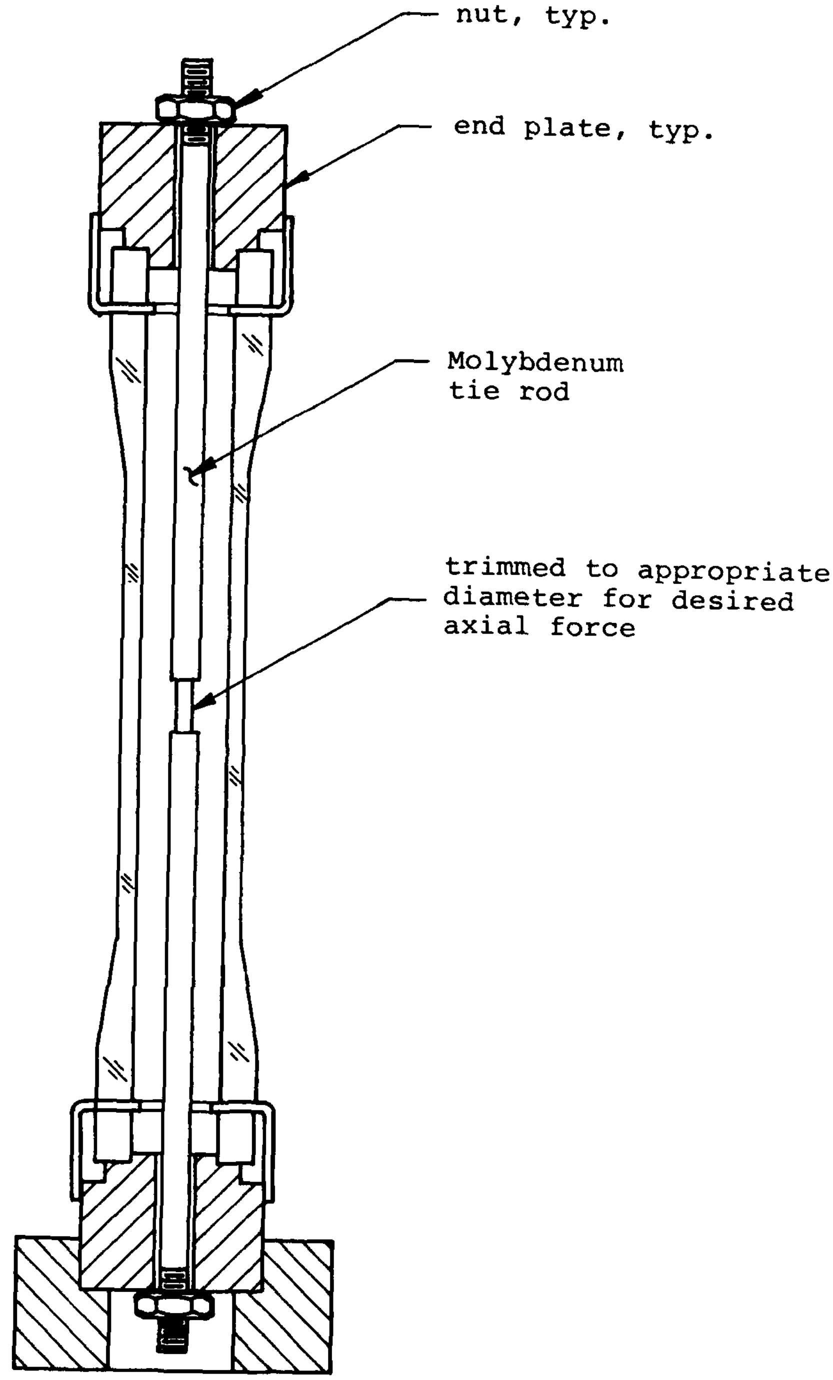


Figure 28. Differential Thermal Expansion Brazing Fixture

molybdenum end plates between which the lamp envelope assembly is sandwiched. The tie rod is threaded at each end so that nuts can be used to initially tighten the assembly before heating. The desired compressive stress can be obtained by adjustment of the tie rod diameter, accomplished in practice by machining a short section of the rod to the appropriate size.

The differential thermal expansion brazing approach was conceived late in the program. Only a limited period of time was available to evaluate it before manufacturing methods for deliverable sixth iteration lamps had to be finalized.

In the first trial with the new fixture a standard envelope assembly was brazed using .0089 mm thick zirconium (much thinner than the standard .0208 mm) and as-received (i.e., unsanded) Kovar cups. The resulting seals were vacuum tight and had very good interfacial wetting. In second and third trials wetting was not nearly as good, however.

In two subsequent trials, thicker zirconium was used. In these samples molten brazing material appeared to have been squeezed out of the seal interface and down the sides of the Kovar cups, causing them to stick to the fixture.

The trial results indicated both the potential advantage of the differential expansion brazing method and the need for more work to establish adequate controls on the process. Unfortunately further work was not possible on the program due to the press of time.

G. Thermal Design Proof Tests

Proof tests were conducted on a prototype sixth iteration lamp operating in the "98 percent" cavity mentioned earlier. The purpose of the tests was to determine the thermal compatibility of the final lamp and cavity configurations. Of particular interest was the lamp heater power required to sustain the desired 72 V lamp operating voltage under atmospheric pressure and simulated zero-g conditions.

Zero-g conditions were simulated by operating the lamp and cavity under a reduced nitrogen pressure of 2.9 kPa. At this reduced pressure free convection heat transfer from the lamp is virtually nonexistent, yet conductive heat transfer through the gas is equal to levels at atmospheric pressure. Thus the gaseous heat transfer effects of a zero-g, 100 kPa nitrogen environment that would prevail in a space borne laser system are accurately reproduced.

The test lamp was filled with a 75%K-25%Rb mixture (plus 100 kPa xenon), the baseline fill at the time. Thermocouples were attached to the cathode end cap and mounting base just ahead of the heater to provide a rough indication of the reservoir temperature. Several thermistors were also attached to the exterior of the cavity. After several test runs at various lamp input powers, operating voltages, and at both nitrogen cover gas pressures, a wrapped nickel foil heat shield was attached to the lamp over the reservoir heater to improve heater efficiency.

Lamp voltage versus heater power curves for operation in atmospheric pressure nitrogen and 2.9 kPa nitrogen are shown in Figures 29 and 30, respectively. The 70 V optimum operating voltage can be sustained with 20 watts of heater power (at 250 W lamp input power) in an atmospheric pressure ambient, safely under the 25 watt design goal. However, at reduced pressure over 18 watts of heater power are required, well above the 10 watt goal for operation under zero-g conditions. Deployment of the heat shield reduces the zero-g heater power to 11 W, still slightly over the design goal.

Other findings were as follows:

1. Operation of the lamp at input powers as high as 300 W and as low as 225 W did not appreciably alter the heater power requirements.
2. Altering the temperature of the pump cavity and/or laser rod heat sink (by reducing coolant flow) had

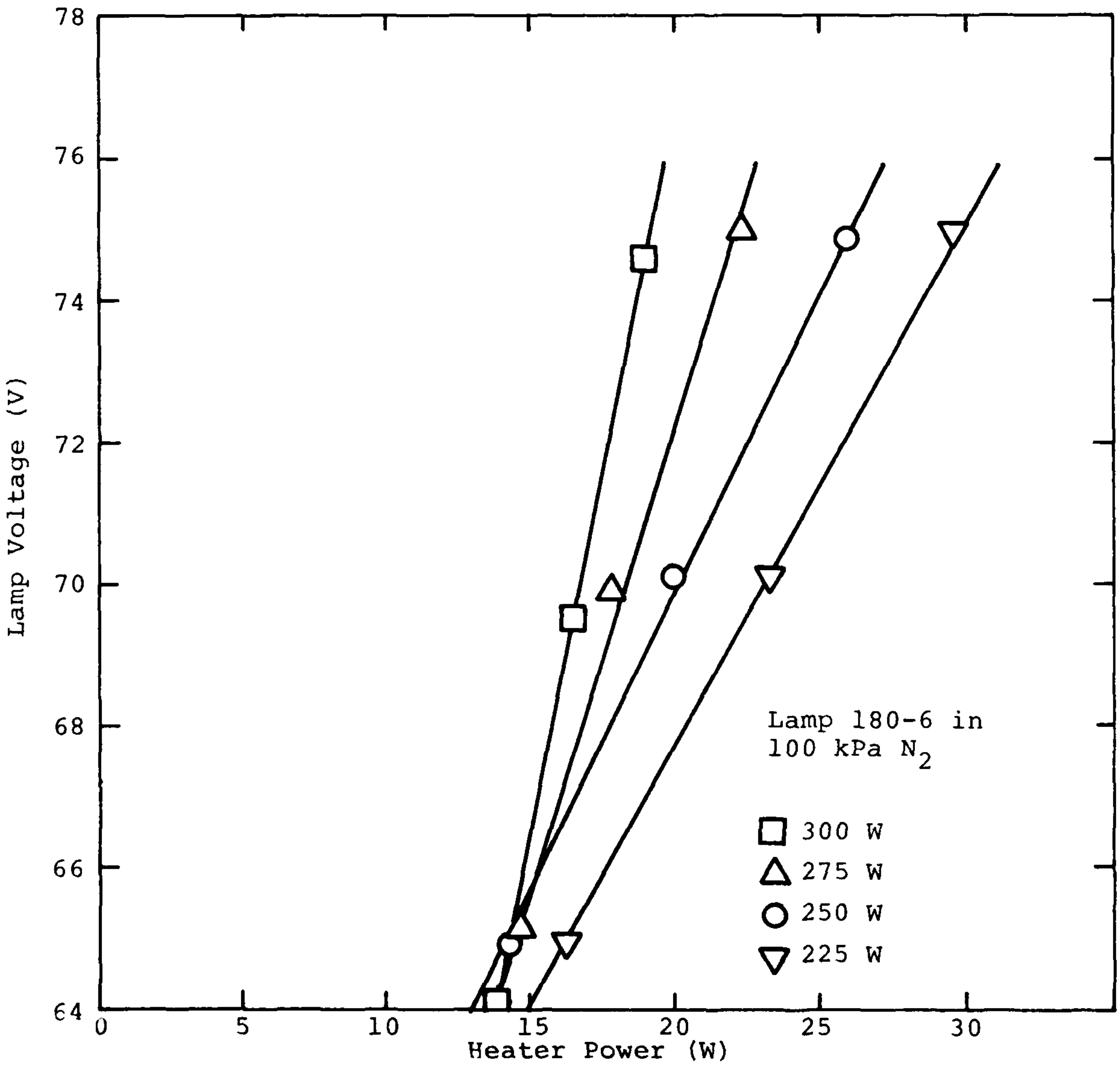


Figure 29. Lamp Voltage vs. Heater Power for Normal Condition

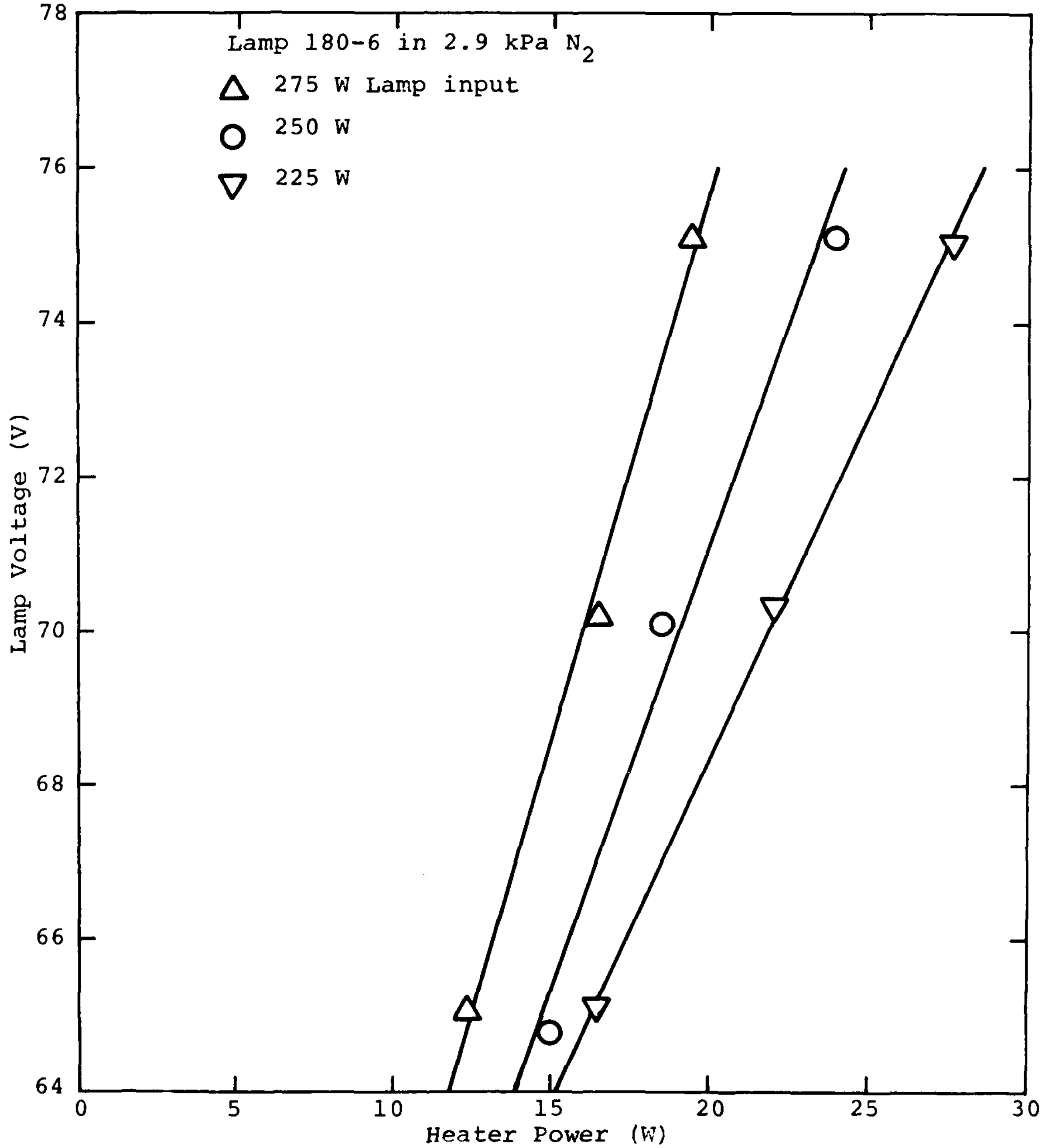


Figure 30. Lamp Voltage vs. Heater Power for Simulated Zero-G Condition

little effect on lamp voltage vs. heater power behavior.

3. Measured temperatures on the lamp were on the order of 550°C.

4. The time constant for lamp voltage adjustment (i.e., in response to an intentional change in heater power) was on the order of 1-2 minutes.

Although the lamp/cavity combination did not satisfy thermal design goals for operation under zero-g conditions, the overall lamp thermal design was judged as satisfactory. Thermal design adjustments necessary to reduce lamp heater power requirements were to be made to the laser cavity (if at all) rather than to the lamp itself.

Later, during acceptance testing of sixth iteration lamps filled with 100% potassium, heater power required to sustain a 72 V optimum voltage (up from 70 V for 75%K-25%Rb lamps) was found to be in excess of 30 W at atmospheric pressure and well over 20 W at reduced pressure. In addition, as mentioned earlier, these lamps suffered from anode end cold spotting, i.e., transport of the alkali metal charge to the anode end of the lamp with attendant loss of lamp voltage controllability. Again corrective action, if any, was to be implemented in the form of cavity modifications. It was found, however, that laser output power was well over required levels even with a lamp operating at 67 V, five volts below optimum, where the voltage would settle out due to the cold spotting effect.

H. Lamp Operating Procedure Optimization

This task was undertaken for the following purposes:

1) To develop a lamp operating procedure that would reduce the elapsed time between the initiation of an operating cycle and achievement of full laser output power

2) To evaluate lamp behavior when operated at various nonhorizontal attitudes, especially with the reservoir (cathode) end up.

Until late in the program lamps were operated very carefully in order to minimize thermal shocks that might result from too rapid heating or cooling. Specifically, once ignited, lamps were operated at a current level of 2 A or less and slowly ramped up to the final 3.5 A current over a period of several minutes. Similarly current was ramped down slowly to 2 A or less before the arc was extinguished. In addition to the excessive time consumed during controlled current ramping, special provisions were required in automatic power supplies to manage the ramp-up and ramp-down phases.

To reduce the elapsed times required to achieve full power, optimum voltage lamp operation and to extinguish the arc and to eliminate the need for power supply logic circuits to ramp current, a revised lamp operating procedure was devised and evaluated. The procedure included the following modifications:

1) Current ramping, per se, was eliminated. Instead the power supply is set to regulate lamp power at 250 W from the onset with current limited to a maximum of 4 A.
2) The arc is extinguished instantaneously by interrupting current to the lamp.

Dozens of operating cycles were performed on a prototype sixth iteration lamp (S/N 182-6) mounted in the "98 percent" cavity using the revised procedure. Elapsed time to full power and optimum voltage was reduced significantly as shown in Figure 31. The high (4 A) initial current did not appear to be harmful to the cathode despite some arc attachment instability and incandescense that typically prevailed for several seconds after

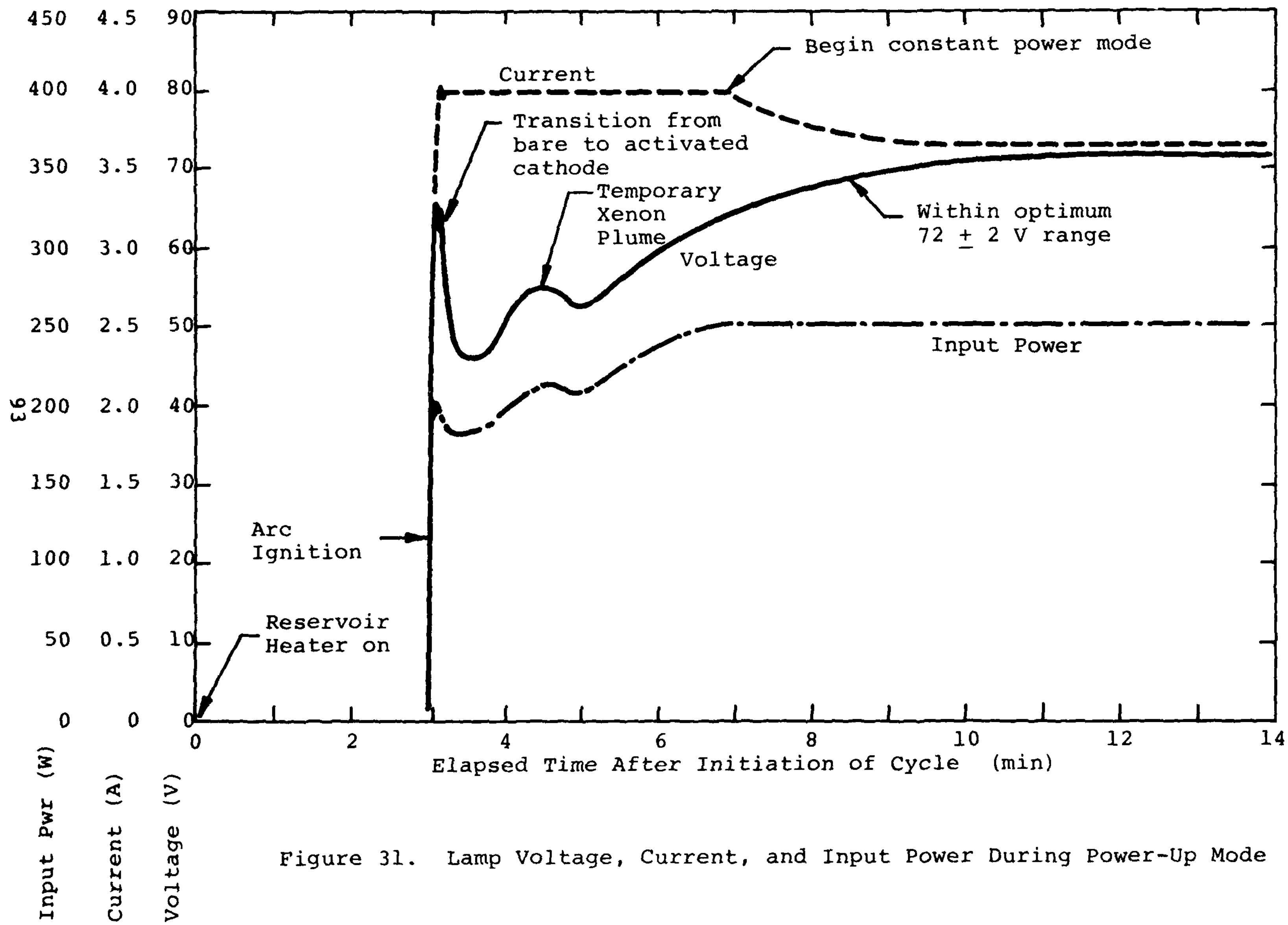


Figure 31. Lamp Voltage, Current, and Input Power During Power-Up Mode

ignition (presumably until the cathode surface became activated with a potassium film). No evidence of structural damage to the lamp associated with the more rapid heating and cooling rates was found.

The time duration and heater power level for preignition operation of the reservoir heater were varied to determine the need for preignition heating. The results (Figure 32) show that the degree of preheating influences the quickness with which the cathode tip becomes activated. Although not absolutely necessary, preheating seemed beneficial and was retained as part of the ignition procedure.

Based on the above results, the revised operating procedure was adopted for use in all future lamp testing.

Lamp attitude effects were of interest because of the possible use of lamp pumped lasers in airborne applications where it might be convenient or necessary to mount the laser transmitter in such a fashion that the lamp would be in a nonhorizontal attitude. There was some concern that gravity effects would predominate over thermal effects within the lamp, causing alkali metal liquid to flow away from the intended reservoir, perhaps even "dripping" through the arc discharge, with attendant loss of lamp voltage controllability.

Variable attitude experiments were conducted with lamp 182-6 in the "98 percent" cavity. A standard operating cycle was run with the lamp and cavity in the standard horizontal attitude. The lamp and cavity were then shifted to a vertical attitude, cathode end down and a second operating cycle performed. The lamp operated in stable fashion although slightly higher reservoir heater power was required to sustain a lamp voltage of 72 V. This was probably due to free convection heat transfer within the lamp away from the cathode end, causing its temperature to decrease.

The lamp and cavity were then reoriented 180° so that the cathode end of the lamp was up. This represented the "worst case"

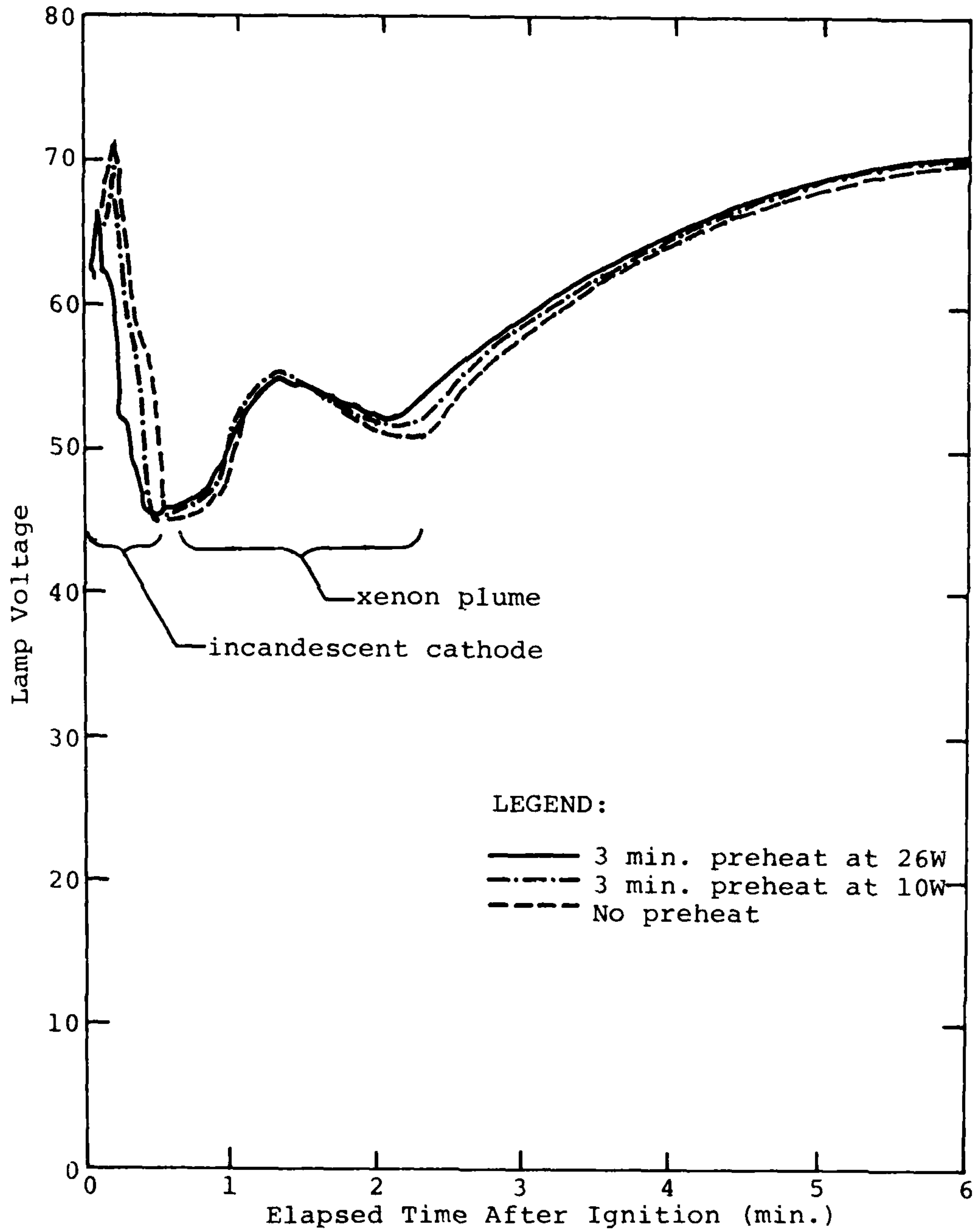


Figure 32. Effect of Lamp Preheat on Post Ignition Behavior

attitude since it maximized the likelihood of alkali metal liquid "dripping" away from the intended reservoir. The lamp ignited and performed normally at 72 V for almost two hours under this condition but then dropped in voltage to approximately 67 V. Lamp voltage could not be increased despite full 40 W reservoir heater power input. It was suspected that the residual potassium liquid had transferred to the anode end of the lamp, probably because in the cathode-up attitude the anode end becomes the coldest spot in the lamp due to free convection heat transfer effects. To transfer the potassium back to the cathode end reservoir the lamp was operated in the standard horizontal attitude at a low heater power (to produce a cathode end temperature well below that of the anode end, thus accelerating the vapor transport process). Once voltage controllability had been regained (indicating that the potassium had returned to the intended reservoir) the lamp was operated horizontally for an additional five hours at 72 V without difficulty. A second cathode-up cycle was then run, this time under a reduced pressure of 2.9 kPa air to eliminate free convection heat transfer external to the lamp. Again the lamp voltage soon dropped to 67 V indicating that heat transfer within the lamp was predominating. The reservoir heater power was reduced to less than 15 W (well below the 30 W level necessary to sustain a lamp voltage of 72 V under ordinary conditions). At this reduced heater power lamp voltage controllability was regained, albiet only at voltages below 67 V. This suggested that potassium was condensing at the cathode end, now presumably at a lower temperature than the anode end, and implied more generally that the potassium liquid would eventually locate at the coldest spot in the lamp, independent of lamp orientation.

The anode cold spotting effect, although apparently brought about by vertical attitude operation, indicated that temperatures at the anode end of the lamp were marginally low in the "98 percent" cavity. Subsequent anode end cold spotting problems with sixth iteration lamps during acceptance testing (Section III-F) confirmed this. As noted earlier any attempts to correct the problem will involve modifications to the cavity design, not to the lamp.

I. Lamp Filling Procedure Optimization

This task had two objectives:

1) To develop a "residue free" technique for loading potassium into lamps, thus preventing subsequent pinch-off failure.
2) To develop a loading technique with which just enough potassium to provide vapor for the arc discharge (but no excess liquid) could be precisely injected into the lamp.

The original technique for filling lamps, used through most of the program, involved refrigerating the alkali metal to harden it, inserting a hollow metal tube into it to pick up a load of material, pushing a solid plunger into the tube until a desired volume equivalent to 10 mg of alkali metal remained, inserting the loaded tube and plunger into the lamp through the fill appendage, ejecting the remaining alkali metal, and then extracting the fill tube and plunger. All of these operations were carried out in a glove box under purified argon gas. The deficiency in this technique was that some alkali metal would remain on the end of the fill tube and rub off onto the inside of the lamp fill appendage when the tube was extracted. It was suspected that this alkali metal residue, subsequently entrapped within the back-welded pinch-off was responsible for several pinch-off failures experienced during lamp operation.

To eliminate the residue problem an improved filling procedure was developed that included two modifications to the original technique. First, instead of ejecting the alkali metal directly into the lamp, it was loaded into a small tubular metal loading capsule, open at one end, which could be wiped off if necessary to eliminate exposed residue and then dropped into the lamp through the appendage. Second, the diameters of the fill tube and plunger were reduced, primarily so that they would fit into the loading capsule, but also to improve the precision with which the volume of alkali metal could be controlled. The original and modified techniques are illustrated in Figure 33.

Six lamps, numbers 209-6, 210-6, 211-6, 212-6, 213-6, and 216-6, were filled with 1 mg each of potassium (10 percent of the standard 10 mg charge) using the modified technique. Each lamp was operated briefly at the end of the program before delivery to the Air Force. All could be operated at the desired 72 volt level with ordinary reservoir heater powers indicating that, as suspected, a 1 mg charge of potassium was more than adequate (see below). No pinch-off failures occurred during the brief predelivery testing. The modified filling technique was adopted as a standard processing step to be employed in future sixth iteration lamps.

The feasibility of loading lamps with just enough potassium to produce an optimum pressure arc discharge (no excess liquid) was also explored. One advantage of such an approach is that the possibility of excess liquid potassium meandering about in the lamp, either under zero-g conditions or in ground or airborne applications with awkward (i.e., cathode up) lamp attitudes, and the resulting uncontrolled lamp voltage flucuations can be avoided. (It should be noted that no experimental evidence for such an effect has ever been obtained; it is, at most, an unlikely possibility that seemed worth addressing.)

A second advantage of the completely vaporized fill approach is that the need for critical control of reservoir temperature is eliminated. By designing the lamp to operate with end temperatures safely in excess of the controlled reservoir temperature in baseline lamps, a super heated (unsaturated) potassium vapor phase would result, still producing an optimally efficient discharge.

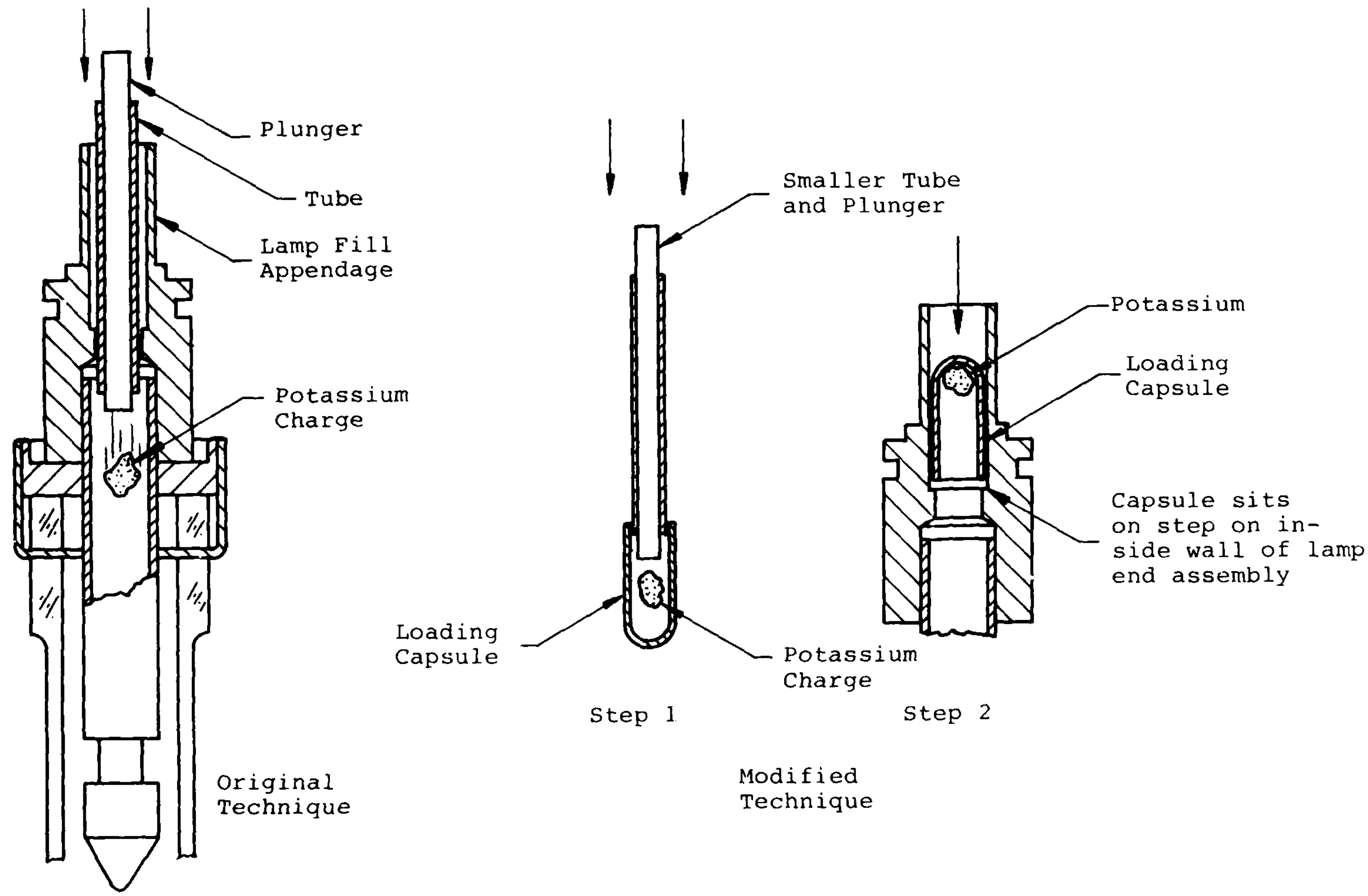


Figure 33. Original and Modified Alkali Metal Filling Techniques

Calculations were performed to determine the amount of potassium needed to produce the optimum discharge. The optimum vapor pressure was assumed to be in the range of 1.3 to 13 kPa (no precise data on lamp cold spot temperature during operation at 72 V or other voltage vs. vapor pressure data were available). This pressure range corresponded with potassium charges of 15 to 150 μg and equivalent volumes of 0.017 to 0.17 μℓ. These amounts of potassium were much too small to be handled with the tube and plunger tool described earlier. Only high precision, micrometer controlled, liquid dispensing syringes seemed suitable for such a task.

Because the melting point of potassium (63°C) is well above room temperature, a provision for keeping the potassium molten during the filling operation was necessary. A coiled nichrome heater element was mounted on a fused quartz tube into which the lamp appendage (or metal fill capsule) and syringe could be inserted.

A calrod-heated block was also obtained for melting potassium in the original glass ampoule. With this setup liquid potassium could be extracted from the ampoule, stored temporarily in the heated syringe bulb, and then dispensed as required.

Unfortunately, it was quickly found that the peculiar wetting and viscosity properties of liquid potassium compromised the operation of the syringe. One type or syringe broke when its thin wire plunger stuck to the pipette. When another type of syringe was tried the potassium initially resisted plunger motion within the bulb and then burst out the pipette in large, uncontrolled droplets.

Press of time prevented any further work on "all-vapor" fills. However, the calculations for amounts of potassium needed for vaporization in the lamp indicated that the standard 10 mg charge was much more than probably required. Consequently, as previously mentioned, several test lamps were filled with a reduced charge (1 mg) using the modified tube/plunger loading technique.

J. Vibration Tests

Two vibration tests were performed during the program. In the first test a third iteration lamp was rigidly mounted in a shake fixture (Figure 34) and subjected to sine and random tests on two axes (parallel and perpendicular to the lamp axis) per the loadings shown in Figure 35. The lamp sustained no apparent damage during these tests and operated normally in a subsequent check-out cycle.

The second vibration test was performed on a group of five sixth iteration lamps, numbers 194-6, 198-6, 203-6, 204-6, and 205-6. Equipment malfunction prevented random vibration tests from being performed. Only sine vibration tests were conducted, again in accordance with the loading curve given above, on three orthogonal axes. The shake fixture used in this test (Figure 36) incorporated standard end mount enclosures from the prototype lamp pumped laser (LPL) cavity, i.e., the lamp was mounted on flexible spring finger collets (see Section V-B) instead of being rigidly clamped as in the first vibration test. Thus this second test provided a more realistic vibration environment for the lamp.

Again the lamps survived the vibration environment without damage. They were subsequently delivered to MDAC-SL for life testing.

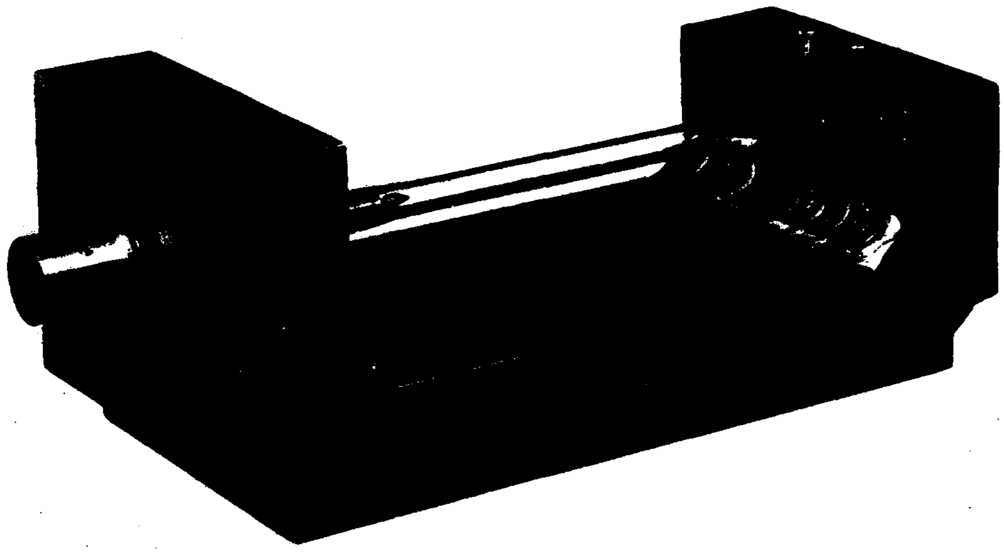
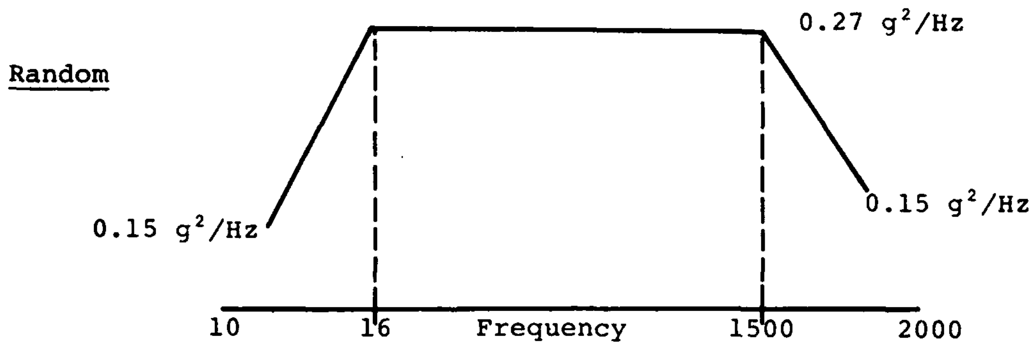


Figure 34. Rigid Mount Vibration Test Fixture



Roll off below 16 Hz at 6DB/octave
Flat 16 Hz to 1500 Hz at 0.27 g^2/Hz
Roll off above 1500 Hz at 6DB/octave

Duration: Two minutes per axis
Axes: Each of two orthagonal
Overall: 22.5 g rms

Sine

10-18 Hz: 1 g 0 to peak
18-70 Hz: 0.06 in. deflection amplitude
70-2000 Hz: 15 g 0 to peak
Sweep Rate: 2 oct/min
3 orthagonal axes

Figure 35. Vibration Test Loading

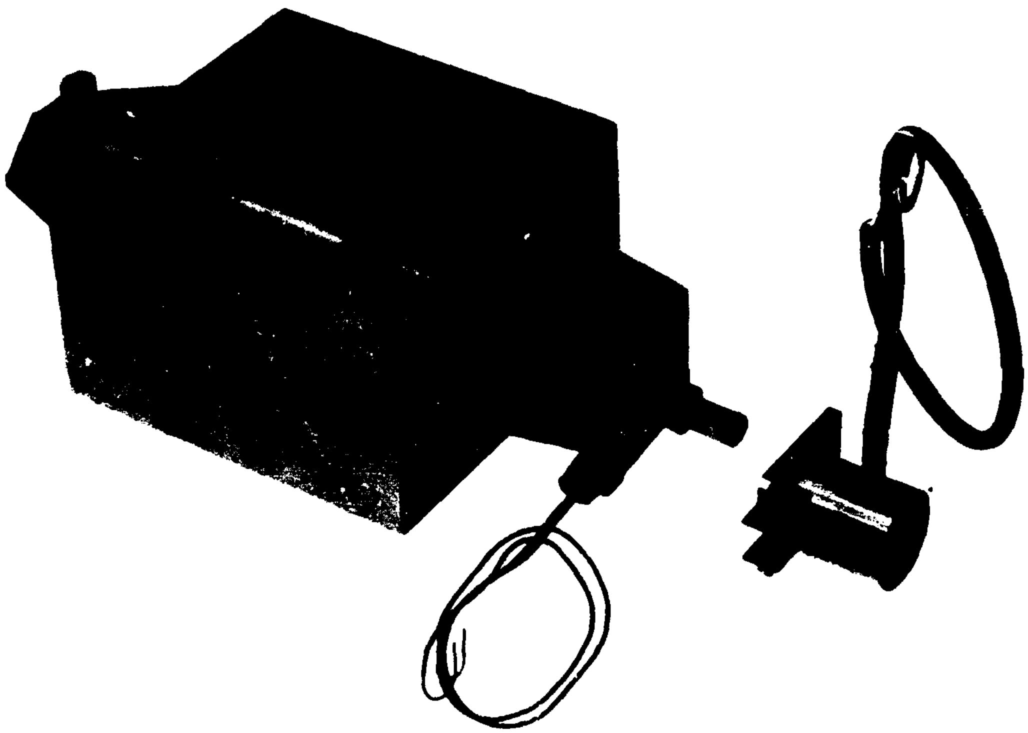


Figure 36. Collet Mount Vibration Test Fixture

SECTION V

LAMP DESIGN SUMMARY

A. Final Configuration

The final sixth iteration lamp design is shown in Figure 37. Key design features are as follows:

- The lamp fill is potassium (1-10 mg) and 100 kPa xenon.
- The envelope material is UV grade, Czochralski-grown, 90°A orientation, cored and polished sapphire.
- The endcaps are Kovar alloy brazed to the envelope with zirconium.
- The electrodes are made of pure tungsten.
- Depleted uranium getters are positioned in various critical locations within the lamp to keep internal oxygen levels low.
- Vitreous or a combination of vitreous and nickel electroplate overcoats are used to protect the brazed end seals and Kovar endcaps from external oxidation.
- An integrally mounted coiled, sheathed heater is employed for alkali metal reservoir temperature control; its input voltage can be linked to lamp voltage in a feedback circuit that keeps the lamp at optimum voltage and potassium pressure.
- Lamp dimensions are as required for installation and operation in the prototype SFTS lamp pumped laser (LPL) developed by GTE-Sylvania.

B. Operating Requirements and Characteristics

1. Mounting Cavity

The potassium lamp is specifically designed for operation in the prototype lamp pumped laser (LPL). The main features of the lamp mounting arrangement in the laser optical pump cavity are depicted in Figure 38. Electrical contact and mechanical support of the lamp are provided by spring finger collets at each end. Locking of the lamp in the correct axial position is achieved by the slot in the removable cathode end enclosure which clamps around the ceramic heater lead insulator on the lamp. The collet

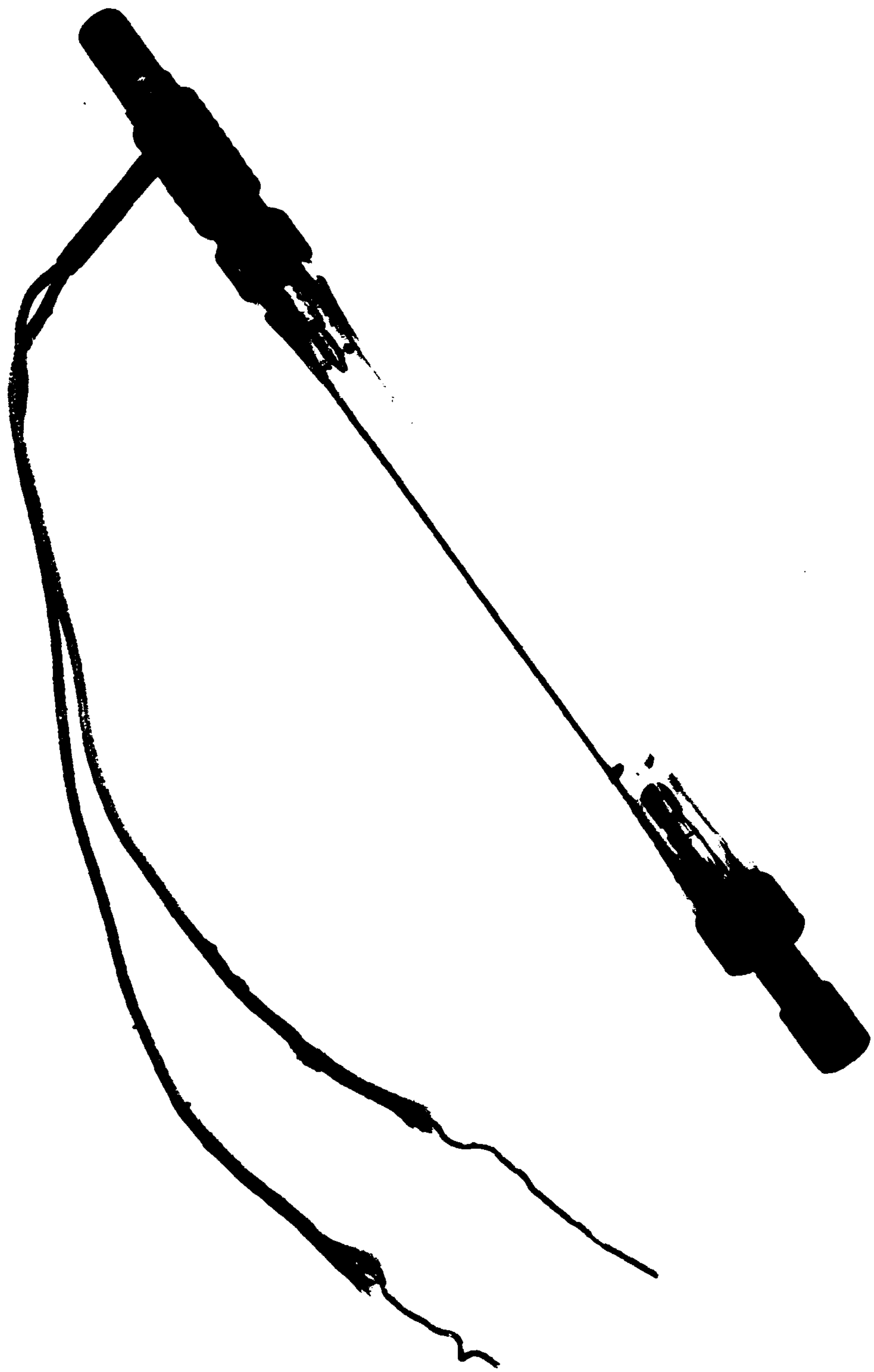


Figure 37. Final Lamp Design Sixth Iteration Lamp

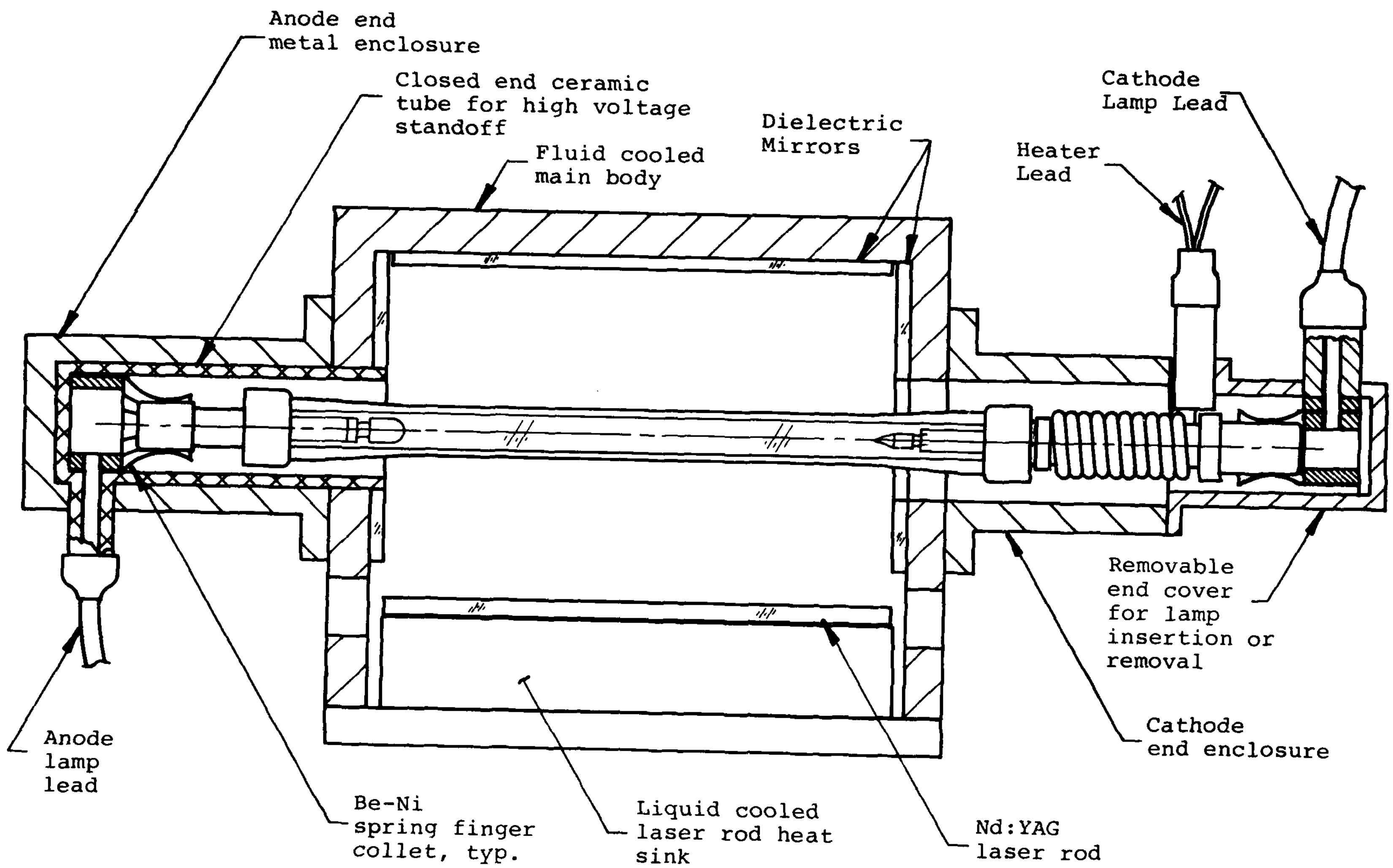


Figure 38. Lamp/Cavity Interfacing Arrangement

mounts allow the lamp to expand and contract in response to heat up and cool down.

The lamp is cooled primarily by radiation heat transfer to the liquid-cooled cavity walls. Minimal conduction from the lamp bases to the mounting collets occurs. A critical thermal design requirement is that cooling of the ends of the lamps be limited so that minimum power to the lamp reservoir heater is needed to sustain the desired lamp voltage and to ensure that temperatures at the anode end of the lamp are at least slightly higher than at the cathode end (necessary for lamp voltage controllability).

In the LPL cavity the anode end of the lamp is electrically hot, the cathode end operating at ground potential although insulated from the cavity enclosure which is also grounded. A tubular ceramic insulator within the anode end enclosure is designed to stand off 16 kV ignition pulses as well as the normal lamp operating voltage.

2. Lamp Ignition and Powering Up

Ignition of the lamp requires a high voltage pulse of at least 11-12 kV applied in parallel with several hundred volts of dc potential from a power supply capable of delivering at least a fraction of an amp of current. Once the arc is established a much lower driving voltage is required, the lamp operating at as low as 40 V prior to powering up and at nominally 72 V for optimum laser pumping.

A typical ignitor and power supply arrangement employs a series trigger transformer and PFN to supply the 16 kV ignition pulses, a separate "boost" dc supply to provide up to 600 V and 0.5 A during the transition from initial breakdown to the stable, controlled arc mode, and a current regulated, 150 V open circuit, 5 A dc supply to drive the arc discharge once it is established. Often, for the sake of convenience, an auxiliary control circuit is used to sense lamp power and supply a driving signal to the regulator circuit to keep the lamp at constant power. A separate voltage regulated power supply is used to drive the lamp reservoir heater.

Because of the negative dynamic resistance of the arc, a resistive ballast (e.g. 10-20 Ω) in series with the lamp is often required. High speed switching supplies have been used successfully without ballasting but must then have relatively low output capacitance.

Details of lamp operation are somewhat arbitrary. To minimize the elapsed time between lamp ignition and full power laser operation, the following lamp starting procedure was adopted: the reservoir heater is operated at the input power required to sustain the 72 V optimal operating voltage during stead state operation for three minutes prior to arc ignition; the lamp is operated at 4 A immediately upon ignition and until lamp voltage increases to 62.5 V (= 250 W) after which current is regulated to maintain constant power at 250 W.

With this procedure the lamp reaches 250 W in less than seven minutes after initiation of the starting sequence (four minutes after arc ignition) and reaches the nominal 72 $\pm$ 2 V operating voltage range in less than ten minutes (see Figure 31).

When the arc is first struck, lamp voltage fluctuates rapidly for a few seconds (due to unstable arc attachment to the initially unactivated cathode tip) and then settles at a value 15-20 volts lower once the cathode tip becomes activated with a potassium film. Shortly later the voltage typically increases by 4-5 volts abruptly due to the temporary existance of a "hybrid arc" or "xenon arc mode". Due to an initially low potassium vapor pressure a plume-like xenon arc develops at the anode tip and extends some distance across the arc gap (Figure 39). The voltage shift associated with this xenon arc mode is apparently due to the difference in the anode work function between bare and potassium-activated states.

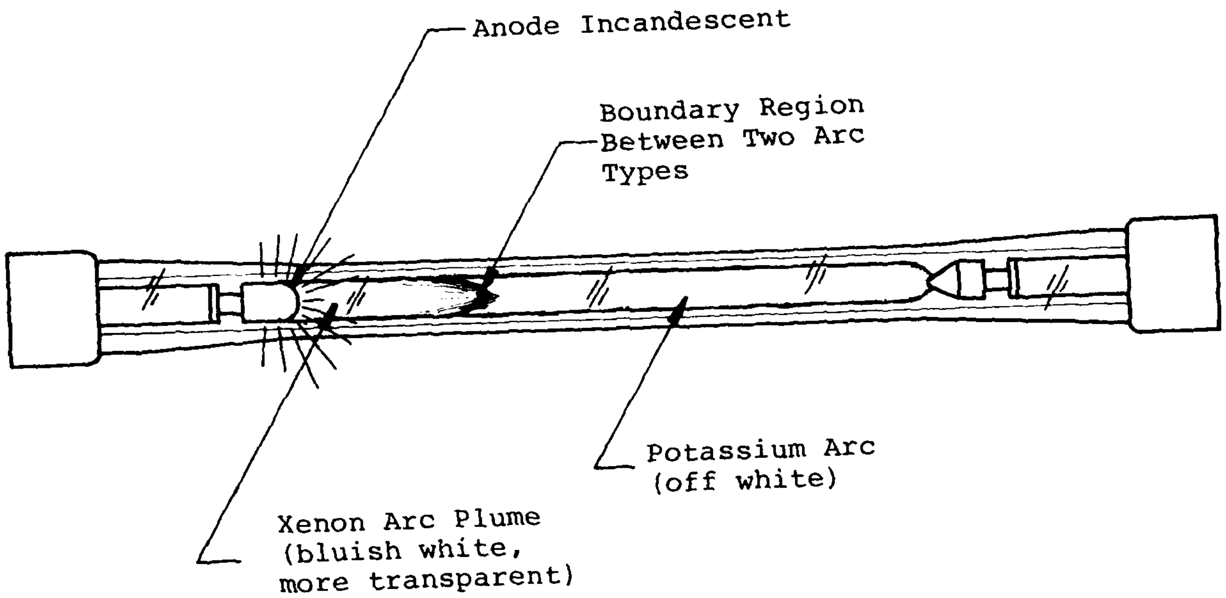


Figure 39. Depiction of Xenon Arc Mode

3. Full Power Operation

At 250 W input power the lamp operates quite stably with only minimal adjustment of heater power required to maintain lamp voltage at 72 $\pm$ 2 V. Operation of the lamp at lower and higher input power levels is feasible. For example, the lamp seems to operate stably and at the nominal voltage at power levels as low as 150 W. No problems were encountered in extended operation at 300 W either.

One concern relating to steady state, full power operation is a drop off of potassium vapor pressure due to inadequate reservoir heater power and the resulting development of the xenon arc plume off the anode tip which, if allowed to persist for more than several minutes, can cause damage to the envelope bore surface. In practice a circuit which automatically shuts off the lamp if lamp voltages fall below 60 V (the xenon arc mode ensues at approximately 58 V) is used to protect unattended lamps from xenon-mode-induced damage.

A second concern is transport of potassium to the anode end of the lamp with resulting fall-off in voltage and loss of voltage control. This problem is avoided by ensuring that the thermal environment in which the lamp is operated keeps the anode end of the lamp hotter than the cathode end when the reservoir heater input power is set to produce the desired lamp voltage. Obviously the anode end cold spotting problem becomes increasingly likely to occur as lamp operating voltage is increased. Since laser pumping efficiency falls off at voltages higher than 75-74 V, there seems to be no reason for lamp operation at higher voltages in any case. Anode end temperature is a strong function of lamp current. Thus, by operating the lamp at higher input power levels (for a given operating voltage) or minimum acceptable voltages (for a given input power) additional temperature margin between anode and cathode ends can be produced.

4. <u>Shut Down</u>

The lamp can be shut off in a variety of ways. However, the most straightforward method is simply to "pull the plug", i.e., interrupt the lamp and reservoir circuits instantaneously. The advantage of this method is that most of the potassium originally in the arc discharge condenses on the envelope wall, thus is immediately available for cathode activation and participation in the arc discharge medium when the lamp is subsequently restarted. Despite the instantaneous drop in lamp input power, the envelope and end seal regions cool slowly enough to prevent any thermal shock damage to the lamp.

5. <u>Lamp Orientation</u>

For terrestial applications lamps can be operated stably in a horizontal orientation or in nonhorizontal attitudes with the cathode end down. The possibility of instability when the lamp attitude is nonhorizontal, cathode end up has not been successfully addressed. Conceivably potassium liquid could "drip" out of the reservoir into the arc region and vaporize, causing lamp voltage flucuations. Brief experiments with anode-up lamp attitudes did not produce such an effect. However, as noted earlier, a lamp cavity thermal design mismatch and resulting anode end cold spotting in the lamp clouded the issue.

C. <u>Radiant Output, Pumping Efficiency</u>

Normal spectral irradiance for a potassium lamp operating at 250 W and 72 V is shown in Figure 40. Principal Nd:YAG excitation bands are shown in the figure. The good match between resonant D-line output from the potassium discharge and the excitation bands explains the high pumping efficiency of these lamps.

Performance of the LPL with a potassium lamp is shown in Figure 41 for different laser conditions. The SFTS program goal of 200 mW laser output power for mode-locked, polarized, TEM_{oo} mode, frequency doubled operation is substantially exceeded. For

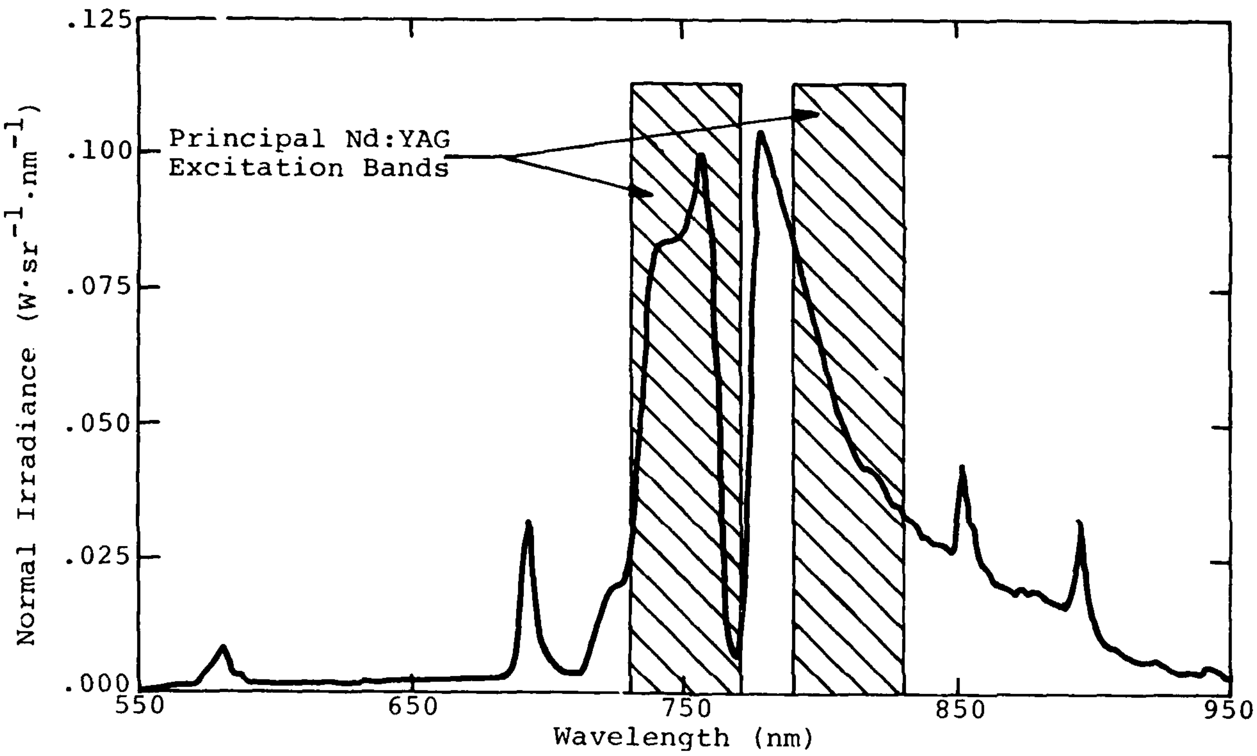


Figure 40. Normal Spectral Irradiance for Potassium Lamp

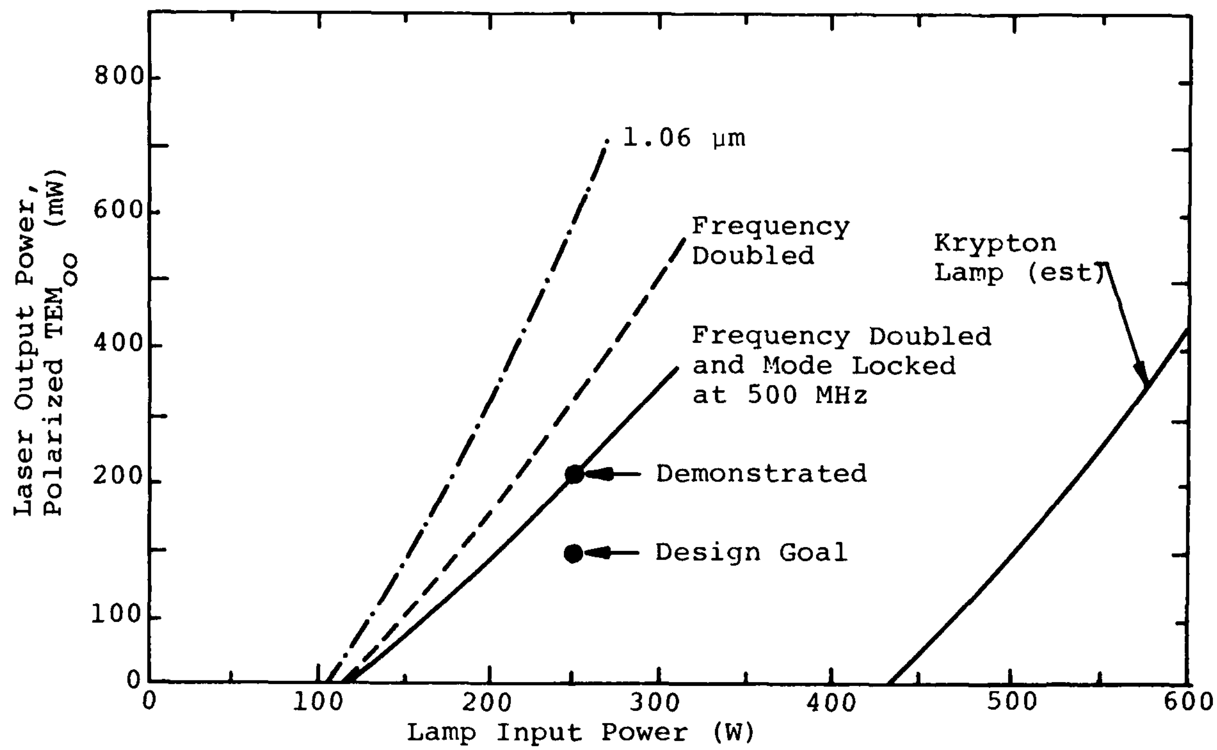


Figure 41. Output of Potassium Lamp Pumped Laser as Function of Lamp Input Power

comparison, the expected performance of the laser with a water-cooled krypton arc lamp is also shown. The superiority of the potassium lamp is dramatic in the low laser power regime of interest for the space communications mission.

An additional advantage of the potassium lamp over a krypton pump source is the excellent laser output stability, i.e., low ripple, resulting from the very stable arc attachment to the cathode in potassium lamps. Nearly all of the measured ripple in laser output is attributable to the dc power supply used to drive the lamp. In contrast significant lamp induced ripple is typical with krypton arc lamps because of inherent short term variations in the cathode fall voltage.

D. Lifetime

As previously mentioned, lifetime statistics on the final sixth iteration lamp has not yet been generated at the end of the subject program. Earlier data, especially for the four experimental pointed tungsten cathode lamps, indicate that the average useful lifetime for potassium lamps exceeds 6000 hours, twice the SFTS program lifetime goal.

The statistical distribution of lifetimes for third and fifth iteration lamps, the two lamp types life tested under the most controlled conditions, were flat and lacked what could be interpreted as genuine "characteristic lifetimes." Lamp failure appeared equally probable at any lifetime, a disturbing thought to be sure. It must be noted, however, that these distributions do not reflect attempts to screen out apparently inferior lamps before testing. The ability to preselect long lived fifth iteration lamps from a general production lot was dramatically demonstrated as noted in Section III-E. With a stringent screening process and improvement in the quality of oxidation protection coatings (given that oxidation-induced leakage was the principal failure mode in lamps on this program) a truncated lifetime distribution with virtually no failures short of 3000 hours should be achievable. Life test results on sixth iteration lamps (with either vitreous overcoat or hybrid coating protection) should confirm this.

E. Space Utility

1. Launch Environment Survivability

As noted in Section IV-J, a rigidly mounted lamp survived random and sine vibration tests to 22 and 15 g levels respectively. A more recent group of sixth iteration lamps also survived the 15 g sine vibration test while mounted in a mechanical simulation of the LPL pump cavity with spring finger collets. Based on these test results it is concluded that the lamp can survive spacecraft launch without difficulty.

2. Materials Degradation

All materials used in the lamp are acceptable for use in space hardware. In addition, all materials on the lamp exterior including the heater lead insulation have low outgassing characteristics so that long term contamination of sensitive optical surfaces in the LPL is avoided.

3. Zero-Gravity Effects

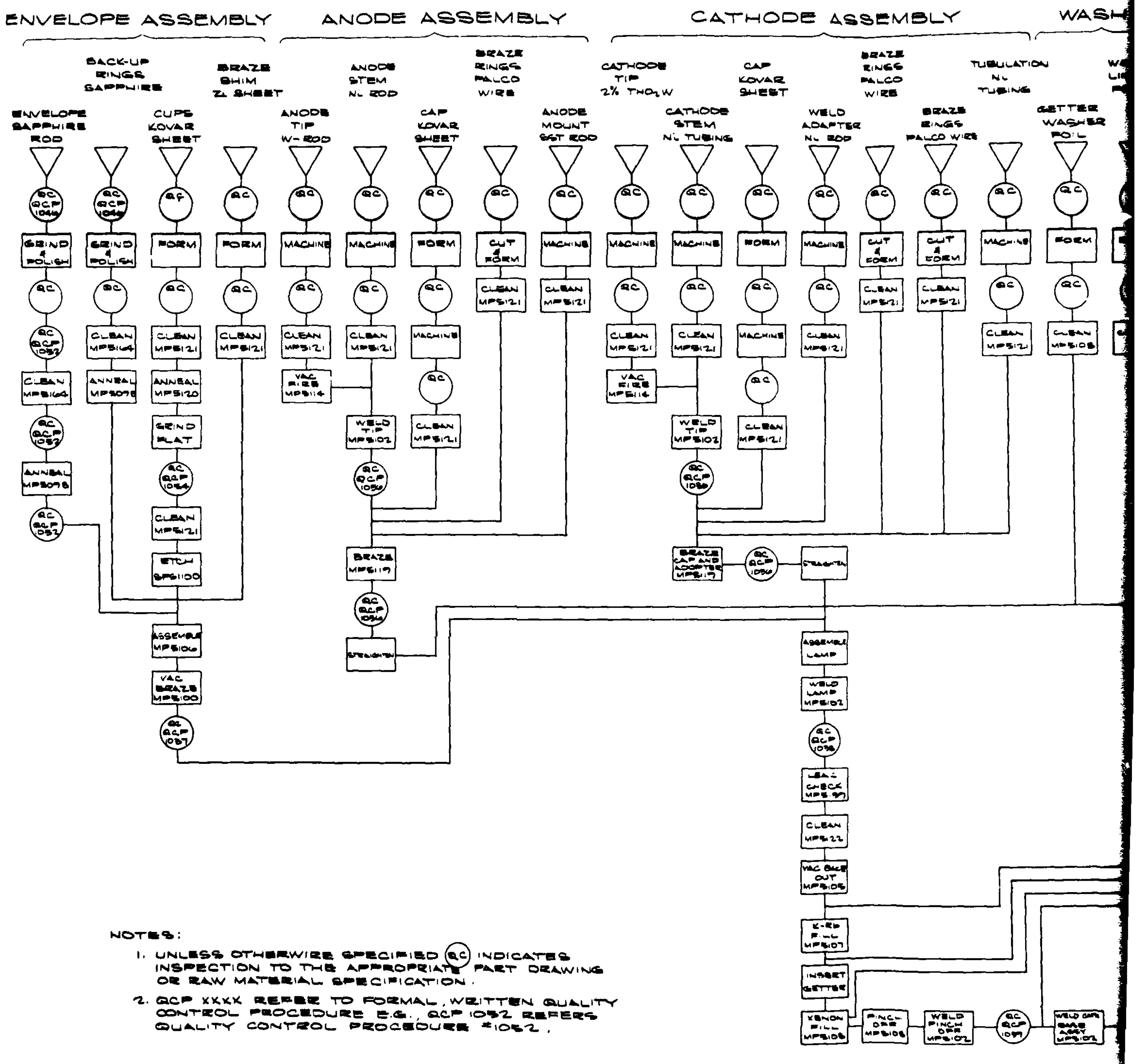
A good deal of thought was given to the possible effects of the zero-gravity environment on lamp operation. It was concluded that the only effect of importance would be loss of free convection heat transfer from the lamp and within the lamp.

Lamps were tested in vacuum to simulate the loss of external free convection cooling. The results showed that somewhat lower but still finite reservoir heater power was required to sustain a given lamp voltage, e.g., 72 V. Controllability of lamp voltage is thus retained.

The absence of free convection within the lamp could not be experimentally simulated. However, general experience with arc lamps indicates that gravity-induced internal convection has a destabilizing influence on the arc. Consequently the absence of gravity ought to represent the best case for arc operation.

F. Reproducibility: Design Documentation

A complete design documentation package exists to ensure that the sixth iteration potassium lamp can be manufactured in essentially identical form in the future. The package includes engineering drawings, materials procurement specifications (indexed in Appendix B), manufacturing and processing specifications (indexed in Appendix C), and quality control procedures (Appendix D). A manufacturing flow chart for the lamp is given in Figure 42.



NOTES:

1. UNLESS OTHERWISE SPECIFIED (QC) INDICATES INSPECTION TO THE APPROPRIATE PART DRAWING OR RAW MATERIAL SPECIFICATION.
2. QCP XXXX REFERS TO FORMAL, WRITTEN QUALITY CONTROL PROCEDURE E.G., QCP 1052 REFERS QUALITY CONTROL PROCEDURE #1052.

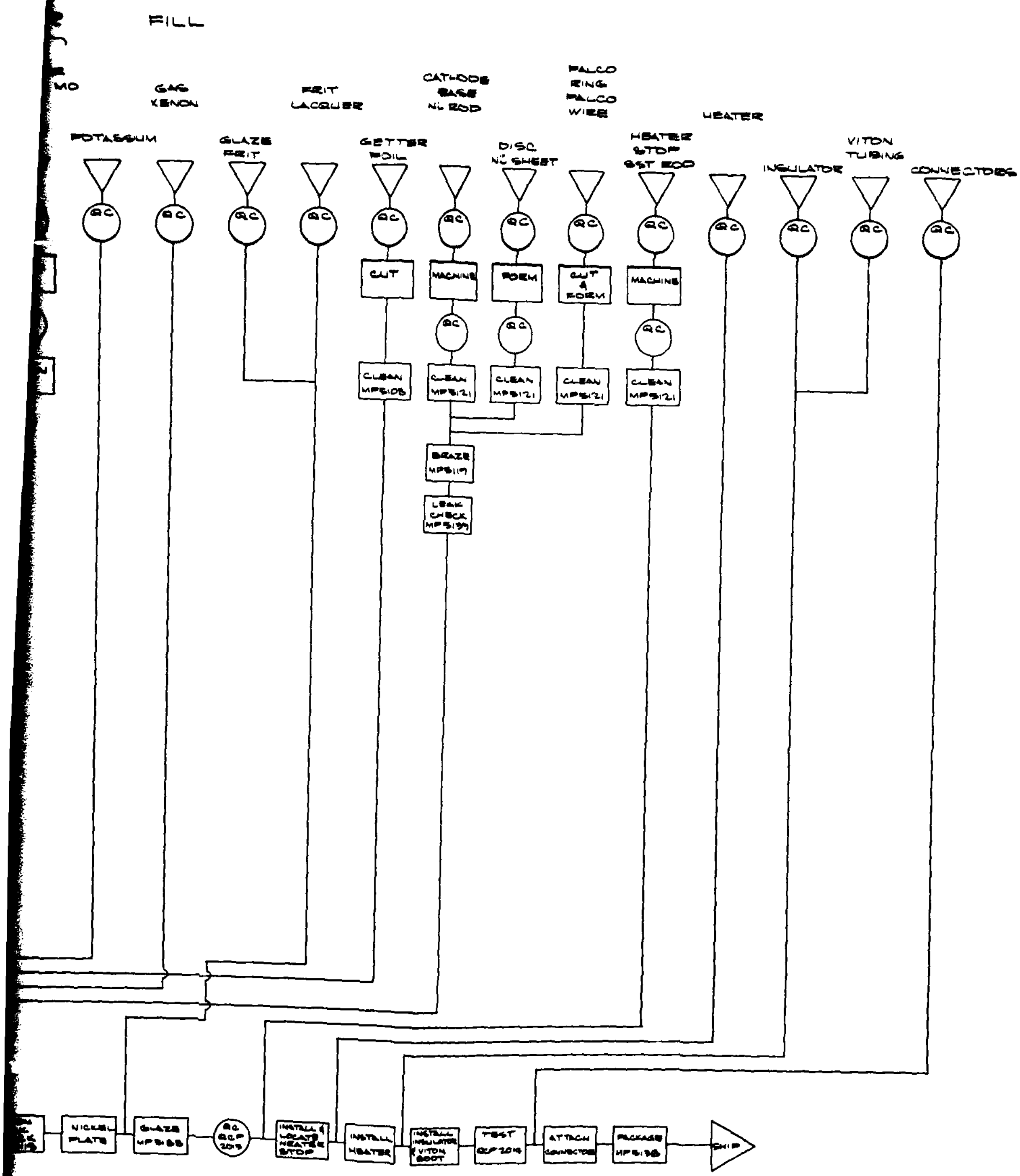


Figure 42

Manufacturing Flow Chart

APPENDIX A

SAPPHIRE ENVELOPE ORIENTATION NOMENCLATURE

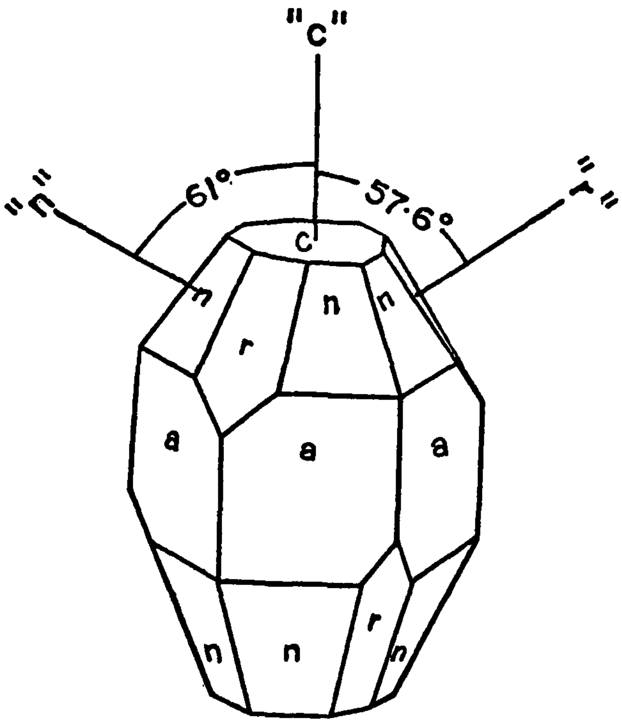
Sapphire (single crystal aluminum oxide) has a quasi-hexagonal crystal structure. Properties of the material vary with crystallographic direction thus it is important to identify the crystal orientation with respect to principal dimensions of the envelope.

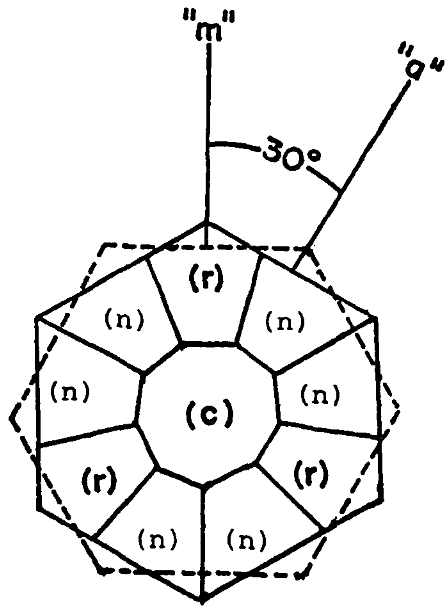
A convention was adopted for this program wherein the principal crystal plane of sapphire parallel to the end planes of the envelope (i.e., normal to the envelope axis) is used to designate the envelope orientation.

The five envelope orientations used on the program and their corresponding end plane crystallographic indices (using the structural, not morphological system) are shown below. The angle in the designations represents the nominal angle between the end plane and the sapphire 0001 plane (or, perhaps more easily envisioned, the angle between the envelope axis and the sapphire c-axis) and the letter corresponds to the commonly used mineralogical symbol for the plane.

Envelope Designation	ILC Code	End Plane Indices
60°R	-001	$10\bar{1}2$
60°N	-002	$2\bar{1}\bar{1}3$
90°A	-003	$11\bar{2}0$
90°M	-004	$10\bar{1}0$
0°	-005	0001

The drawing attached shows the various principal planes of sapphire more clearly. For a more detailed and rigorous treatment of the subject, the reader is referred to M.L. Kronberg, "Plastic Deformation of Single Crystals of Sapphire: Basal Slip and Twinning," <u>Acta Metallurgica</u> 5 507-524 (1957).


"c"
"n"
61°
57·6°
"r"
c
n
n
n
r
a
a
a
n
n
r
n


"m"
"a"
30°
(r)
(n)
(n)
(n)
(c)
(n)
(r)
(r)
(n)
(n)

APPENDIX B

PROCUREMENT SPECIFICATION INDEX

Material Name	Specification Number	Modifier (to be added to purchase order)	Remarks and References
200 Nickel Rod	ASTM B160-70	ILC Q-6	
200 Nickel Tubing	ASTM B161-70	ILC Q-6	
Stainless Steel Rod	ASTM A582-75	Type 303, ILC Q-6	UNS Designation: S30300
Stainless Steel Bar	ASTM A493-74	Type 302, 304, or 305; ILC Q-6	
Stainless Steel Wire	ASTM A581-75	Type 303, ILC Q-6	
Molybdenum	ASTM B386-74	ILC Q-6	
Kovar	ASTM F15-69	ILC Q-6	
Zirconium Sheet	ILC PS 1023		ASTM B352-67, Grade R-1
Uranium Foil	ILC PS 1024		Reactor Experiments, Inc.
2% Thoriated Tungsten Rod	ILC PS 1025		ASTM B410-68
Palco	ILC PS 1026		WESGO
270 Nickel	ILC PS 1027		INCO
K-Rb Alloy	ILC PS 1028		Mausteller et al
Xenon	ILC PS 1029		Cryogenic Rare Gas
Sapphire	ILC PS 1032		PS 1006
Tungsten Rod	ILC PS 1033		ASTM B410-68
Glaze	ILC PS 1058		
Frit Lacquer	ILC PS 1063		

APPENDIX C

MANUFACTURING SPECIFICATION INDEX

ILC Number	Title
MP 5098	Sapphire Annealing Procedure
MP 5099	Flattening of Nickel and Kovar Cups
MP 5100	Zirconium Brazing of Sapphire to Kovar
MP 5102	TIG Weld Procedure for K-Rb Lamp Assemblies and Subassemblies
MP 5105	Bakeout in Glove Box Vacuum Furnace
MP 5106	Orientation of Sapphire Parts in Seal Assemblies
MP 5107	Alkali Metal Loading Procedure
MP 5108	Pump and Fill Procedure for K-Rb Lamps
MP 5109	Final Bakeout in Glove Box Vacuum Furnace
MP 5113	Vacuum Furnace Operation
MP 5114	Vacuum Fire of Electrode Tips
MP 5115	Xenon Leak Test
MP 5119	Palco Braze Procedure
MP 5120	Clean Firing and Annealing of Kovar Parts
MP 5121	Solvent Cleaning of Lamp Parts
MP 5122	Post Leak Check Cleaning Procedure
MP 5125	Storage
MP 5128	Glove Box Preventative Maintenance Procedure
MP 5138	Packing for Shipment
MP 5139	Hermeticity Test - Helium
MP 5145	Lamp Test Plan
MP 5164	Chemical Cleaning of Sapphire
MP 5188	Glaze Application
MP 5201	Hand Lapping of Kovar Seal Cups
MP 5202	Cup Flatness Test
SPS 1100	Bright Dipping of Nickel-Iron Alloys

APPENDIX D

QUALITY CONTROL PROCEDURE INDEX

ILC Number	Title
QCP 1036	Metal Parts Subassembly Inspection
QCP 1037	Inspection of Envelope Assembly
QCP 1038	Inspection of Welded Lamp Assembly
QCP 1039	Inspect Pinch-Off Weld
QCP 1046	Crystal Orientation and Labeling
QCP 1052	Visual Inspection of Sapphire Lamp Envelopes
QCP 2014	Acceptance Test
QCP 2015	Test of Glaze Coating

APPENDIX E

LAMP LOG FOR PHASE I AND PHASE II

LAMP LOG

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo-sition	Lifetime* Cycles	Lifetime* Hours	Remarks
01	N1X	37027	60°	75-25	66	Efficiency tests	AF	?	?	No life data available.
02	N2P	37027	60°	75-25	100	Laser use	MDAC-E	?	?	No life data available.
03	N3P	37027	60°	75-25	100	Laser use	Sylvania	?	?	No life data available.
04	---	37027	60°	---	---	1st iteration life tests	---	--	--	Scrapped, bad end weldment.
05	---	37027	60°	---	---	1st iteration life tests	---	--	--	Scrapped, defects in envelope.
06	N6L	37027	60°	0-100	100	1st iteration life tests	ILC	43	453	Oxidation leaks in braze blush areas.
07	N7L	37027	60°	0-100	100	1st iteration life tests	ILC	42	465	Oxidation leaks in braze blush areas.
08	N8X	37027	60°	75-25	39	Efficiency tests	AF	?	?	No life data available.
09	N9E	37027	60°	75-25	100	Power supply tests	ILC	100	50	Envelope shear fracture at seals.
10	N10X	37027	60°	75-25	13	Efficiency tests	AF	?	?	No life data available.
11	N11X	37027	60°	75-25	100	Efficiency tests	AF	?	?	No life data available.
12	N12E	37027	60°	90-10	100	Envelope study	ILC	15	665	Testing stopped, had small BPCC.
13	---	37027	60°	---	---	Envelope study	---	--	--	Scrapped, bad end weldment.
14	N14E	37027	60°	90-10	100	Envelope study	ILC	15	694	Testing stopped, had small BPCC.
15	N15E	37027	60°	0-100	100	Envelope study	ILC	20	792	Testing stopped, large BPCC.
16	N16E	37027	60°	90-10	100	Envelope study	ILC	5	348	Testing stopped, large BPCC.
17	N17E	37027	60°	90-10	100	Envelope study	ILC	3	64	Fillet leak and envelope shear fracture.

*Parenthesized lifetime data indicate lamp still operable.

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Disposition	Lifetime* Cycles	Lifetime* Hours	Remarks
18	---	37027	60°	---	---	Envelope study	---	--	--	Scrapped, bad end weldment.
19	---	37028	60°	---	---	1st iteration life tests	---	--	--	Scrapped, poor seal wetting.
20	---	37028	60°	---	---	1st iteration life tests	---	--	--	Scrapped, poor seal wetting.
21	K21L	37028	60°	75-25	100	1st iteration life tests	ILC	3	42	Fillet leak (zirconium-nickel hybrid).
22	K22L	37028	60°	75-25	100	1st iteration life tests	ILC	5	142	Testing stopped, xenon mode frosting analyzed.
23	N23P	37027	60°	75-25	100	Laser use	MDAC	14	100	Testing stopped, envelope discoloration analyzed.
24	K24L	37028	60°	75-25	100	1st iteration life tests	ILC	21	561	Seal parted (zirconium-nickel hybrid).
25	N25X	37191	60°	90-10	100	Efficiency tests	AF	?	?	4x6.5 envelope; no life data available.
26	N26X	37191	60°	75-25	100	Efficiency tests	AF	6	15	4x6.5 envelope; fillet leak; no data available.
27	N27X	37225	60°	75-25	100	Efficiency tests	AF	?	?	4x6.5 envelope; 47.5 mm arc; no life data avail.
28	N28X	37027	60°	90-10	100	Efficiency tests	AF	7	19	Shear fracture in envelope at seal.
29	---	37223	60°	---	---	Efficiency tests	---	--	--	Scrapped, bad pinch-off.
30	N30X	37223	60°	75-25	100	Efficiency tests	AF	?	?	47.5 mm arc; no life data available.
31	N31E	37193	60°	90-10	100	Envelope study	ILC	6	621	4x7.5 envelope; envelope shear fracture at seals.
32	---	37193	60°	---	---	Envelope study	---	--	--	Scrapped, poor seal wetting.
33	N33E	37027	90°	90-10	100	Envelope study	ILC	16	1034	Would not restart, envelope dissected.
34	N34E	37203	90°	90-10	100	Electrode study	ILC/ MDAC	(40)	(440)	Pointed tungsten cathode; testing terminated.

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo-sition	Lifetime* Cycles	Lifetime* Hours	Remarks
35	N35E	37027	90°	90-10	100	Envelope study	ILC	21	797	Envelope shear fracture at seal.
36	---	37027	90°	---	---	Open	ILC	--	--	Envelope assembly in storage.
37	N37E	37198	0°	90-10	100	Envelope study	ILC	7	805	Would not restart, envelope dissected.
38	---	37198	0°	---	---	Open	ILC	--	--	Envelope assembly in storage.
39	N39E	37027	60°	90-10	100	Envelope study	ILC	2	113	Testing stopped, large BPCC.
40	---	37027	60°	---	---	Thermal design study	---	--	--	Scrapped, leak in end weldment.
41	---	37135	60°	---	---	PES lamp development	---	--	--	Scrapped, leak in CVD seal.
42	---	37135	60°	---	---	PES lamp development	---	--	--	Scrapped, cracked frit seal.
43	N43E	37027	60°	90-10	100	Envelope study	ILC	6	462	Gas polished envelope; leak in end weldment?
44	N44E	37027	60°	90-10	100	Thermal design study	ILC	(2)	(7)	Testing stopped, annular heater shorted.
45	N45E	37205	60°	90-10	100	Electrode study	ILC	3	3	Molybdenum weight fell on lamp and smashed it.
46	N46E	37206	60°	90-10	100	Electrode study	ILC	(12)	(12)	Pointed tungsten cathode;
47	N47E	37027	60°	90-10	100	Envelope study	ILC	13	836	Testing stopped, BPCC.
48	N48E	37204	60°	90-10	100	Electrode study	ILC	22	1800	Pointed tungsten cathode; envelcpe shear fracture at seal.
49	N49L	37189	60°	90-10	100	2nd iteration life tests	ILC	1	17	Pinch-off failure.
50	N50L	37189	60°	90-10	100	2nd iteration life tests	ILC	24	225	Fillet leak.
51	N51L	37201	60°	90-10	100	2nd iteration life tests	ILC	27	201	Fillet leak.

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo-sition	Lifetime* Cycles	Lifetime* Hours	Remarks
52	N52L	37201	60°	90-10	100	2nd iteration life tests	ILC	7	93	Fillet leak.
53	K53L	37199	60°	90-10	100	2nd iteration life tests	ILC	128	1315	Fillet leak.
54	K54L	37199	60°	90-10	100	2nd iteration life tests	ILC	116	1266	Leak through BPCC.
55	K55L	37199	60°	90-10	100	2nd iteration life tests	ILC	--	--	Used for power supply checks, life not moni-tored.
56	K56L	37199	60°	90-10	100	2nd iteration life tests	ILC	14	145	Fillet leak (zirconium-nickel hybrid).
57	K57L	37199	60°	90-10	100	2nd iteration life tests	ILC	--	--	Would not start.
58	K58L	37199	60°	90-10	100	2nd iteration life tests	ILC	15	122	Cathode damaged by "dry" start.
59	K59S	37244	90°	75-25	100	Laser experiments	Sylvania	?	?	No life data available
60	K60S	37244	90°	75-25	100	3rd iteration life tests	ILC	--	--	Rejected, marginal seal.
61	---	37244	90°	---	100	3rd iteration life tests	---	--	--	Scrapped, poor seal wetting.
62	---	37244	90°	---	---	3rd iteration life tests	---	--	--	Scrapped, poor seal wetting.
63	K63S	37244	90°	75-25	100	Laser experiments	Sylvania	38	161	Pinch-off failed.
64	---	37244	90°	---	---	3rd iteration life tests	---	--	--	Seal leak after welding, poor wetting.
65	K65S	37244	90°	75-25	100	3rd iteration life tests	MDAC-E	29	312	Fillet leak, cup wall ground too thin.
66	K66S	37244	90°	75-25	100	3rd iteration life tests	MDAC-E	169	1610	Fillet leak.
67	K67S	37244	90°	75-25	100	3rd iteration life tests	ILC	(30)	(160)	Used for thermal design tests.
68	---	37244	90°	---	100	3rd iteration life tests	---	--	--	Scrapped, poor seal wetting.
69	K69S	37244	90°	75-25	100	3rd iteration life tests	MDAC-E	100	1303	Fillet leak.
70	---	37244	90°	---	100	3rd iteration life tests	---	--	--	Scrapped, poor seal wetting.

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo-sition	Lifetime* Cycles	Lifetime* Hours	Remarks
71	---	37244	90°	---	---	3rd iteration life tests	---	--	--	Scrapped, poor seal wetting.
72	---	37244	90°	---	---	3rd iteration life tests	---	—	--	Scrapped, poor seal wetting.
73	K73S	37244	90°	75-25	100	3rd iteration life tests	MDAC	(444)	(5250)	Still operable.
74	---	37244	90°	---	---	3rd iteration life tests	---	---	---	Scrapped, poor seal wetting.
75	K75S	37244	90°	75-25	100	3rd iteration life tests	MDAC	(?)	(150)	Control lamp for fluores-cent output & laser tests.
76	K76S	37244	90°	75-25	100	3rd iteration life tests	AF	---	---	Poor seals, used to pump EFM laser at MDAC-E.
77	K77S	37244	90°	75-25	100	3rd iteration life tests	MDAC	200	2160	Fillet leak.
78	K78S	37244	90°	75-25	100	3rd iteration life tests	MDAC	170	1800	Fillet leak.
79	K79E	37244	90°	90-10	100	Envelope study	ILC	16	784	Would not restart, en-velope frosted.
80	K80S	37244	90°	75-25	100	3rd iteration life tests	MDAC	32	255	Leak in mismatched (Kovar-Nickel) weldment.
81	K81E	37244	90°	90-10	100	Envelope study	ILC	26	397	Cathode stem melted due to deactivation.
82	---	37244	90°	---	---	3rd iteration life tests	---	--	--	Scrapped, poor seal wetting.
83	K83E	37244	90°	75-25	100	Electrode study	ILC	--	--	In storage.
84	K84S	37244	90°	75-25	100	3rd iteration life tests	MDAC	(393)	(5471)	Still operable.
85	K85S	37244	90°	75-25	100	3rd iteration life tests	MDAC	123	1200	Fillet leak.
86	K86P	37276	60°	75-25	100	Laser use	Sylvania	?	?	4x6.5 envelope; no life data available
87	K87P	37276	60°	75-25	100	Laser use	Sylvania	?	?	4x6.5 envelope; no life data available
88	K88P	37276	60°	75-25	100	Open	ILC	---	---	4x6.5 envelope; in storage.

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo-sition	Lifetime* Cycles	Lifetime* Hours	Remarks
89	K89P	37276	60°	75-25	100	Laser use	MDAC-E			4x6.5 envelope; no data available.
90	K90P	37276	60°	75-25	100	Open	ILC	--	--	4x6.5 envelope; in storage.
91	K91L	37287	90°	75-25	100	4th iteration life tests	ILC	141	4368	Apparent leak; volt. down
92	K92L	37287	90°	75-25	100	4th iteration life tests	ILC	29	493	Weldment leak.
93	K93L	37287	90°	75-25	100	4th iteration life tests	ILC	271	5441	Weldment leak.
94	K94L	37287	90°	75-25	100	4th iteration life tests	ILC	(14)	(104)	Not tested extensively; in storage.
95	N95X	37243	60°	75-25	100	Efficiency study	AF	?	?	No life data available.
96	N96E	37273	60°	75-25	100	Electrode study	ILC	--	--	Tungsten-4%ThO_2 pointed cathode.
97	N97E	37270	60°	75-25	100	Electrode study	ILC	--	--	Pinch-off failed before testing.
98	N98X	37243	60°	75-25	100	Efficiency study	AF	?	?	No life data available.
99	N99E	37270	60°	75-25	100	Electrode study	ILC	6	36	Pointed tungsten-2%ThO_2 cathode; shear fracture at seal.
100	N100E	37273	60°	75-25	100	Electrode study	ILC	(11)	(1638)	Tungsten-4%ThO_2 pointed cathode.
101	K101L	37286	0°	75-25	100	4th iteration life tests	ILC	56	590	Weldment leak.
102	K102L	37286	0°	75-25	100	4th iteration life tests	ILC	21	251	Testing stopped, BPCC analyzed.
103	K103L	37286	0°	75-25	100	4th iteration life tests	ILC	(208)	(5303)	Still operable;envelope very frosty from start.
104	K104L	37285	90°	75-25	100	4th iteration life tests	ILC	66	991	5x7.5 envelope; weldment leak.
105	K105L	37285	90°	75-25	100	4th iteration life tests	ILC	(141)	(4467)	5x7.5 envelope; still operable.
106	K106L	37285	90°	75-25	100	4th iteration life tests	ILC	55	1363	5x7.5 envelope; pinch-off failure, has BPCC.

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo-sition	Lifetime* Cycles	Lifetime* Hours	Remarks
107	K107P	37276	90°	75-25	100	Laser use	MDAC	?	?	4x6.5 envelope; no life data available.
108	K108P	37276	90°	75-25	100	Laser use	MDAC	?	?	4x6.5 envelope; no life data available.
109	K109P	37276	90°	75-25	100	Laser use	MDAC	?	?	4x6.5 envelope; no life data available.
110	K110P	37276	90°	75-25	100	Laser use	MDAC	?	?	4x6.5 envelope; no life data available.
111	K111E	37287	90°	75-25	100	Processing Experiment	ILC	(16)	(1356)	300° post fill bake
112	K112E	37287	90°	75-25	100	Processing Experiment	ILC	--	--	300° post fill bake
113	K113E	37287	90°	75-25	100	Processing Experiment	ILC	--	--	No post fill bake
114	K114E	37287	90°	75-25	100	Processing Experiment	ILC	(18)	(1991)	No post fill bake
115	K115E	37308	60°	75-25	100	Cathode Eval	ILC	(51)	(1609)	Oxide Cathode
116	K116E	37308	60°	75-25	100	Cathode Eval	ILC	(51)	(1608)	Oxide Cathode
117			60°	75-25	100	-	ILC			-
118	K118E	37244	60°	75-25	100	Envelope Eval	ILC	(16)	(325)	Vernuiel Sapphire
119	K119E	37244	60°	75-25	100	Envelope Eval	ILC	(21)	(1073)	Vernuiel Sapphire
120	K120E	37287/ 37319	60°	75-25	100	For evaluation of thermal design mod at anode end	ILC	?	?	No life data available
121	K121E	37287/ 37319	60°	75-25	100	For evaluation of thermal design mod at anode end	ILC	?	?	No life data available
122										Start # skipped by mistake
123	123-4	37287	90°	100-0	100	For laser tests, eval. 100K fill	MDAC	?	?	No life data available

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo-sition	Lifetime* Cycle	Lifetime* Hours	Remarks
124	124-4	37287	90°	100-0	100	For laser tests, eval. 100K fill	MDAC	?	?	No life data available
125	125-4	37287	90°	75-25	100	For laser tests, base-line fill	MDAC	?	?	No life data avialable
126	126-X	37244/ 37279	60°	75-25	100	For eval. of new heater design	ILC SYL	-	-	Has incandescent cathode
127	127-X	37244/ 37279	60°	75-25	100	For eval. of new heater design	ILC	-	-	Had incandescent cathode
128	128-4	37287	90°	75-25	100	Laser tests	MDAC	?	?	No life data available
1]9	129-4	37287	90°	75-25	100	Laser tests	MDAC	?	?	No life data available
130	--	37320	90°	-	-	5th It. life tests	-	-	-	Scrapped, bad seals
131	--	37320	90°	-	-	5th It. life tests	-	-	-	Scrapped, bad seals
132	--	37320	90°	-	-	5th It. life tests	-	-	-	Scrapped, bad seals
133	133-5	37320	90°	75-25	100	5th It. life tests	MDAC	168	3000	Failed, weldment leak
134	134-5	37320	90°	75-25	100	5th It. life tests	MDAC	-	2950	Failed, weldment leak
135	135-5	37320	90°	75-25	100	Fluorescent output standard	-	-	-	Has small crack in tube near seal
136	136-5	37320	90°	75-25	100	5th It. life tests	-	-	-	Cathode incandescent during burn-in
137	137-5	37320	90°	75-25	100	5th It. life tests	MDAC	(272)	(6851)	Still operable
138	138-5	37320	90°	75-25	100	5th It. life tests	-	-	-	Failed during burn-in pinch-off leak
139	139-5	37320	90°	75-25	100	5th It. life tests	MDAC	-	2683	Failed, weldment leak
140	140-5	37320	90°	75-25	100	5th It. life tests	MDAC	(29)	(117)	Fluorescent test control lamp

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo- sition	Lifetime* Cycle	Lifetime* Hours	Remarks
141	141-5	37320	90°	75-25	100	5th It. life tests	MDAC	99	1877	Failed, weldment leak
142	142-5	37320	90°	75-25	100	5th It. life tests	MDAC	(200)	(6495)	Still operable
143	143-5	37320	90°	75-25	100	5th It. life tests	MDAC	199	5511	Failed, weldment leak
144	144-5	37320	90°	75-25	100	5th It. life tests		-	-	Cathode incandescent during burn-in
145	145-5	37320	90°	100-0	100	5th It. life tests	ILC	-	-	Not used
146	146-5	37320	90°	100-0	100	5th It. life tests				Anode very crooked, not used
147	147-5	37320	90°	100-0	100	5th It. life tests	MDAC	125	4660	Failed, weldment leak
148	148-5	37320	90°	100-0	100	5th It. life tests		-	-	Cathode incandescent during burn-in
149	149-5	37320	90°	100-0	100	5th It. life tests	MDAC	82	613	Failed, leak in cathode end weldment
150	150-0	37320	90°	100-0	100	5th It. life tests		-	-	Output low, not used
151	151-X	37340	60°	75-25	100	Thermal design proof test	SYL	?	<100	Has pointed tungsten cathode; failed in weldment
152	152-X	37340	60°	75-25	100	Thermal design proof test	ILC	-	115	Has pointed W cathode; envelope cracked after water leak in bell jar
153	153-X	37341	60°	75-25	100	Cathode life test	ILC	(140)	(5424)	W cathode
154	154-5	37341	60°	75-25	100	5th It. life test	ILC	-	-	In storage
155	155-5	37320	90°	75-25	100	5th It. life test	MDAC	(252)	(6411)	Still operable
156	156-5	37320	90°	75-25	100	5th It. life test	MDAC	(319)	(5878)	Still operable

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo-sition	Lifetime* Cycle	Lifetime* Hours	Remarks
157	157-5	37320	90°	75-25	100	5th It. life test	-	-	-	Pinch off failed during burn-in, scrapped
158	158-5	37320	90°	75-25	100	5th It. life test	-	-	-	Cathode incandescent during burn-in
159	159-5	37320	90°	75-25	100	5th It. life test	-	-	-	Cathode incandescent during burn-in
160	160-5	37320	90°	100-0	100	5th It. life test	MDAC	(179)	(6306)	Still operable
161	161-5	37320	90°	100-0	100	5th It. life test	MDCA	(194)	(6221)	Still operable
162	162-5	37320	90°	100-0	100	5th It. life test	MDAC	(220)	(5308)	Failed; envelope fracture adjacent to cathode
163	163-X	37341	60°	75-25	100	Cathode life test	ILC	(131)	(6070)	Has pointed W cathode
164	164-X	37341	60°	75-25	100	Cathode life test	ILC	(128)	(5556)	Has pointed W cathode
165	165-X	37341	60°	75-25	100	Cathode life test	ILC	(124)	(5576)	Has pointed W cathode
166	166-X	37341	60°	75-25	100	Cathode life test	ILC	(15)	(100)	Voltage low; testing discontinued
167	167-5	37320	90°	75-25	100	Laser tests	MDAC	?	?	No life data available
168	168-5	37320	90°	75-25	100	Laser tests	MDAC	?	?	No life data available
169	169-X	37340	60°	75-25	100	Thermal design proof tests	ILC	?	?	---
170	170-X	37340	60°	75-25	100	Thermal design proof tests	ILC	?	?	---
171	171-5	37320	90°	75-25	100	Miscellaneous tests	ILC	?	?	---
172	172-5	37320	90°	75-25	100	Miscellaneous tests	ILC	?	?	---
173	173-5	37320	90°	75-25	100	Miscellaneous tests	ILC	?	?	---

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo- sition	Lifetime* Cycle	Lifetime* Hours	Remarks
174	174-6	37354	90°	75-25	100	Laser tests	SYL	?	?	No life data available
175	175-6	37354	90°	75-25	100	Laser tests	SYL	?	?	No life data available
176	176-6	37354	90°	75-25	100	Laser tests	MDAC	?	?	No life data available
177	177-6	37354	90°	75-25	100	Laser tests	MDAC	?	?	No life data available
178	178-6	37354	90°	75-25	100	Laser tests	MDAC	?	?	No life data available
179	179-6	37354	90°	75-25	100	Fluorescent test calibration standard	ILC	-	-	Infrequently used
180	180-6	37354	90°	75-25	100	Thermal design tests	ILC	-	-	
181	181-6	37354	90°	100-0	100	Miscellaneous tests	AF/ILC	-	-	
182	182-6	37354	90°	100-0	100	Miscellaneous tests	AF/ILC	-	-	
183	--	37354	90°	--	-	Thermal design tests (pure K fill)	TBD	-	-	Scrapped, bad lamp/base weld
184	184-6	37354	90°	100-0	100	Miscellaneous tests	AF/ILC	-	-	
185	--	37354	90°	--	-	---	Scrap	-	-	Scrapped, bad seal
186	--	37361	90°	--	-	---	Scrap	-	-	Brazed to DTE fixture
187	--	37361	90°	--	-	---	Scrap	-	-	Brazed to DTE fixture
188	--	37361	90°	--	-	---	TBD	-	-	Marginally wetted seals
189	--	37361	90°	--	-	---	TBD	-	-	Marginally wetted seals
190	--	37361	90°	--	-	---	TBD	-	-	Marginally wetted seals
191	191-6	37361	90°	100-0	100	Laser tests	SYL	(10)	(85)	
192	192-6	37361	90°	100-0	100	Laser tests	SYL	(7)	(56)	

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo-sition	Lifetime* Cycle	Lifetime* Hours	Remarks
193	193-6	37361	90°	100-0	100	Laser tests	SYL	(9)	(58)	
194	194-6	37361	90°	100-0	100	6th It. life test	MDAC	?	?	On life test
195	--	37361	90°	100-0	100	---	TBD	-	-	K in pinch-off
196	--	37361	90°	100-0	100	---	TBD	-	-	K in pinch-off
197	--	37361	90°	100-0	100	---	Scrap	-	-	Dropped and broken during glazing
198	198-6	37361	90°	100-0	100	Life test	MDAC	?	?	On life test
199	--	37361	90°	100-0	100	---	TBD	-	-	K in pinch-off
200	--	37361	90°	--	-	---	Scrap	-	-	Seals cracked due to brazing run abort
201	--	37361	90°	--	-	---	Scrap	-	-	Seals cracked due to brazing run abort
202	--	37361	90°	--	-	---	Scrap	-	-	Seals cracked due to brazing run abort
203	203-6	37361	90°	100-0	100	Life test	MDAC	?	?	On life test
204	204-6	37361	90°	100-0	100	Life test	MDAC	?	?	On life test
205	205-6	37361	90°	100-0	100	Life test	MDAC	?	?	On life test
206	206-6	37361	90°	100-0	100	---	Scrap	-	-	Apparent pinch-off leak during burn-in
207	207-X	37361	60°	Vacuum	100	Electrical tests in laser	SYL	-	-	
208	--	---		--	-	---	Scrap	-	-	Poor braze wetting, leaker
209	209-6	37361	90°	100-0	100	Reduced fill exp.	TBD	-	-	Ready for delivery

Start No.	Serial No.	Assembly Drawing	Envelope Type	K-Rb Fill	Xenon Pressure (kPa)	Intended Use	Dispo- sition	Lifetime* Cycle	Lifetime* Hours	Remarks
210	210-6	37361	90°	100-0	100	Reduced fill exp.	TBD	-	-	Ready for delivery
211	211-6	37361	90°	100-0	100	Reduced fill exp.	TBD	-	-	Ready for delivery
212	212-6	37361	90°	100-0	100	Reduced fill exp.	TBD	-	-	Ready for delivery
213	213-6	37361	90°	100-0	100	Reduced fill exp.	TBD	-	-	Ready for delivery
214	--	---	-	--	-	---	Scrap	-	-	Poor braze wetting, leaker
215	--	37361	90°	--	-	Reduced fill exp.	Scrap	-	-	Poor braze wetting, leaker
216	216-6	37361	90°	100-0	100	Reduced fill exp.	AF	-	-	Ready for delivery

REFERENCES

1. Noble, L., et. al, ILC Technology, Inc., "Optical Pumps for Lasers," ECOM-0035-F, AD 724733, May 1971.

2. Noble, L., ILC Technology, Inc., "Pump Lamps for Nd:YAG Lasers," AFAL-TR-72-50, AD 893914, February 1972.

3. Noble, L. and Kretschmer, C., ILC Technology, Inc., "Pump Lamps for Nd:YAG Lasers", AFAL-TR-74-107, AD 922391, July 1974.

4. Anderson, N., ILC Technology, Inc., "K-Rb Laser Pump Lamp", AFAL-TR-75-112, ADB 009019, November 1975.

5. Anderson, N., ILC Technology, Inc., "Laser Pump Lamp," AFAL-TR-76-66, ADB 017604, February 1977.

6. Ibid, pp. 16-18.

7. Wiederhorn, S. M., "Fracture of Sapphire," J. Am. Ceram. Soc., 52, 485-491 (1969).

8. Becher, P. F., "Fracture-Strength Anisotropy of Sapphire," ibid, 59, 59-61 (1976).

9. Firestone, R. F., and Heuer, A. H., "Creep Deformation in 0 Sapphire," ibid, 59, 24-29, (1976).

10. Rice, R. W. and Becher, P. F., "Comment on Creep Deformation of 0 Sapphire," ibid, 60, 186-188 (1977).

11. Heuer, A. H. and Firestone, R. F., "Reply to 'Comment on Creep Deformation of 0 Sapphire,'" ibid, 60 188-180 (1977).

12. Newman, M. and Forray, M., "Thermal Stresses in Cylindrical Shells," Machine Design, June 10, 1963.

13. Priest, D. and Talcott, R., "Thermal Stresses in Ceramic Cylinders Used in Vacuum Tubes," Am. Ceram. Soc. Bull., 38 99-105 (1959).

14. Anderson, N., "Basal Plane Cleavage Cracking of Synthetic Sapphire Arc Lamp Envelopes," J. Am. Ceram. Soc., 62, 108-109, (1979).

15. Wright, D. A., "A Survey of Present Knowledge of Thermionic Emitters," Proc. Inst. Elec. Engrs., 100, Part 3, 125-142 (1953).

*U.S.Government Printing Office: 1979 — 657-002/723